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Volume I - Summary

FINAL REPORT,

EVALUATION OF ADVANCED

COMBUSTION CHAMBER (TOROID)

January 1963

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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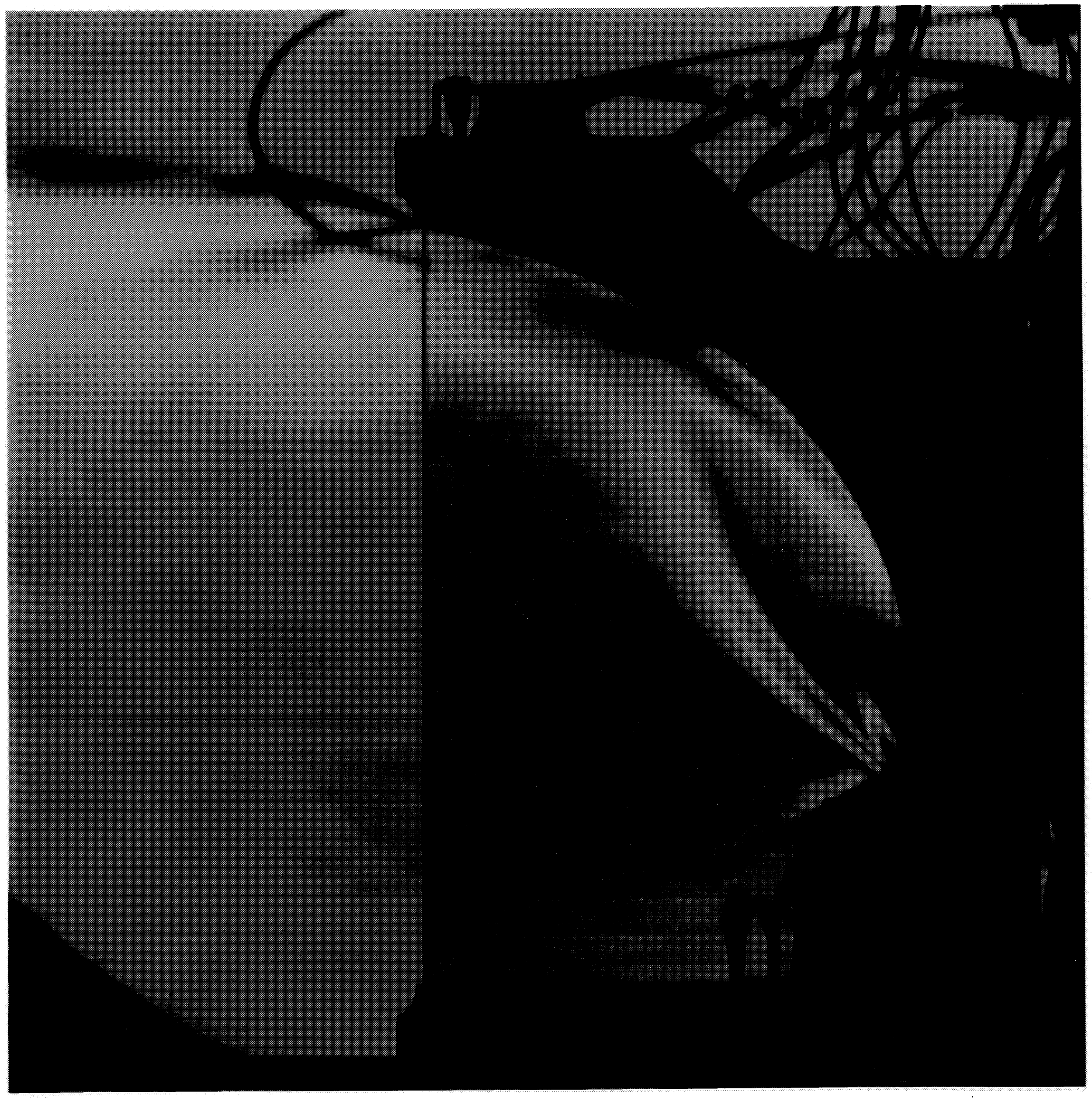
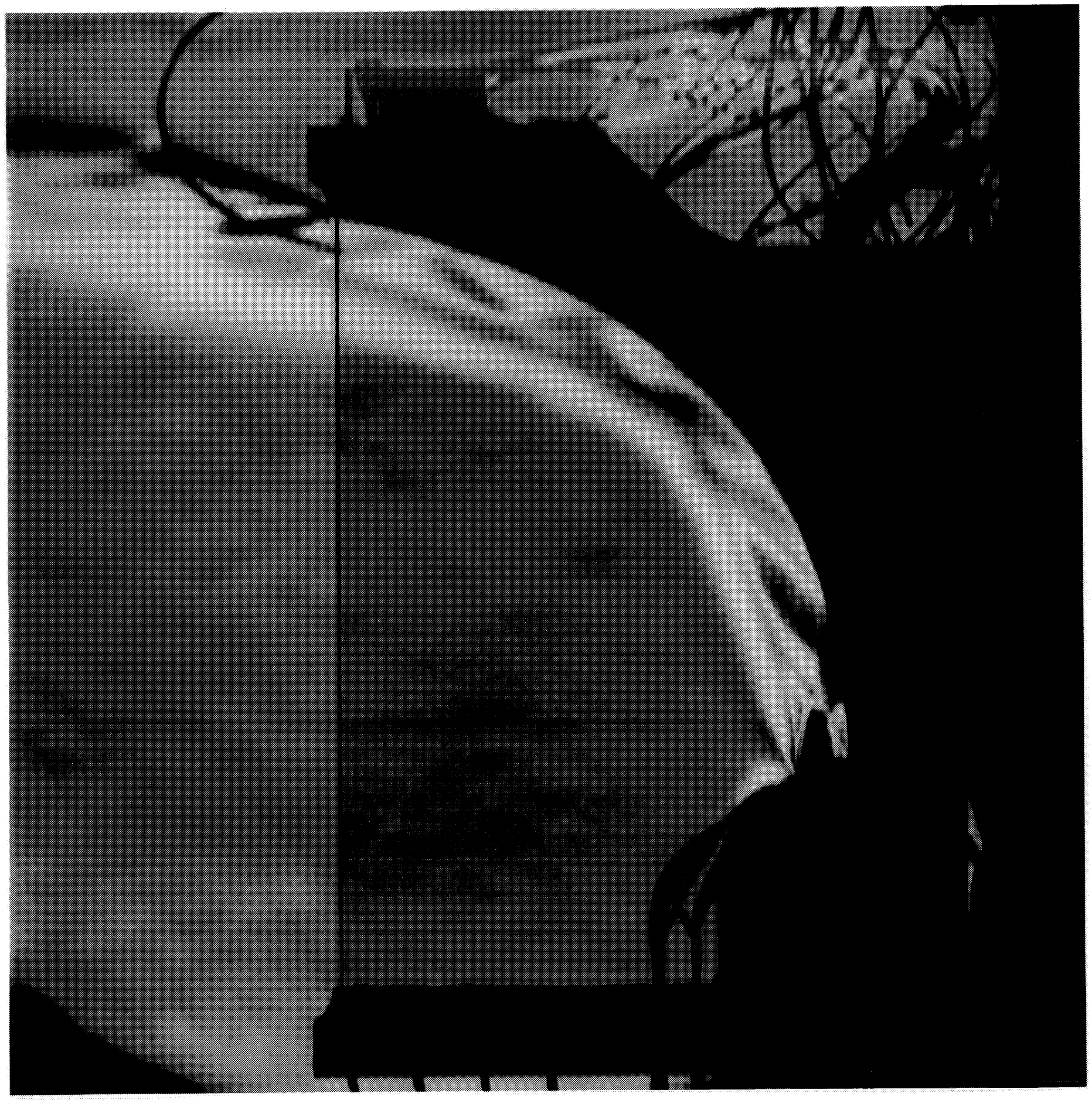


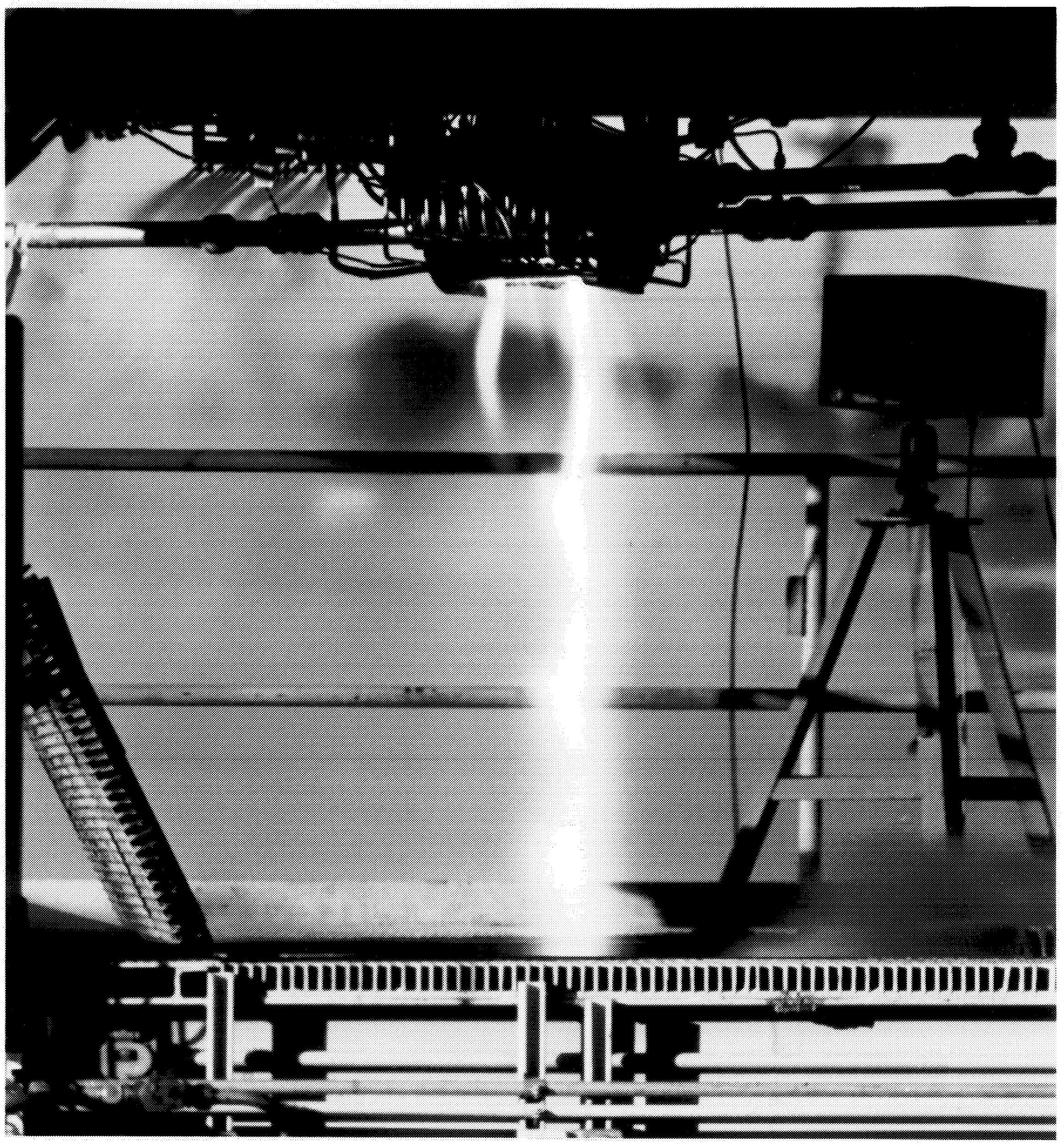
Frontispiece A. Cold-Air Testing of Continuous Throat Model

Operation of a continuous throat model at low pressure ratio is shown by Schlerien photography. Flow convergence and recompression are clearly indicated.



Frontispiece B. Cold-Air Testing of Toroidal Model at Low Pressure Ratio

The comparative performance of toroidal and continuous throat configurations has been evaluated by Schlerien photographs, pressure profiles and thrust measurements. Over 200 cold flow tests have been completed.



Frontispiece C. Toroidal Model at Transition into Mainstage

The toroidal model has completed seven successful firings. Valuable heat transfer and material data have been gained and performance efficiency has approximated 100 percent.

FOREWORD

This report, describing studies of advanced combustion chamber construction conducted from April 1962 to November 1962, was prepared under G.O. 8319 in compliance with National Aeronautics and Space Administration Contract NAS 8-4013.

ABSTRACT

The results of studies and tests conducted to evaluate the feasibility of the toroidal chamber are presented. Analytical aerodynamic studies and cold-flow model testing were used to determine the effect of the toroidal concept of chamber performance. These studies evaluated effects of tube spacing, contraction ratio, and shape. Theoretical and heat transfer stress studies, supplemented by a hot firing demonstration program, determined concept operational capabilities. The applications of regenerative and film coolant methods were evaluated for several propellant combinations. Many tube materials were tested, and experimental heat flux data were compared to analytical predictions.

(Unclassified Abstract)

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INTRODUCTION

During the past few years, the advantages of the annular thrust chamber configurations such as the plug and expansion deflection (E-D) have been advanced. Because of their unique expansion process, these nozzles provide performance and length advantages over the conventional bell-type configurations. The annular shape of the combustion chamber, as opposed to the cylindrical combustion chamber of the bell configurations, also endows these advanced nozzles with the potential of simple sectioning or segmentation. This convenience has been shown to decrease the time and cost requirements for development of the new large engines.

The use of the annular nozzles also introduces certain problem areas. One such problem is associated with the combustion chamber. Theoretically, maximum performance can be achieved by a continuous annular throat configuration. However, use of such configuration introduces serious weight problems. This fact is illustrated in Fig. 1 . As shown, the use of a continuous annular throat, for either a plug or E-D type of configuration, requires considerable structural support on the lower portion of the combustion chamber. This support is not only necessary to maintain structural integrity of the unit but also to minimize any deviations in throat dimensions. (Because of the long narrow throats required for annular configurations, throat tolerances are several orders of magnitude more critical than for more conventional bell configurations.)

In addition to the structural problems involved in constructing the continuous annular throat, the design of a simple cooling network to cool both the skirt and chamber requires considerable effort. Thus it appears that maximum performance can only be attained with considerable compromise in weight and cooling network simplicity.

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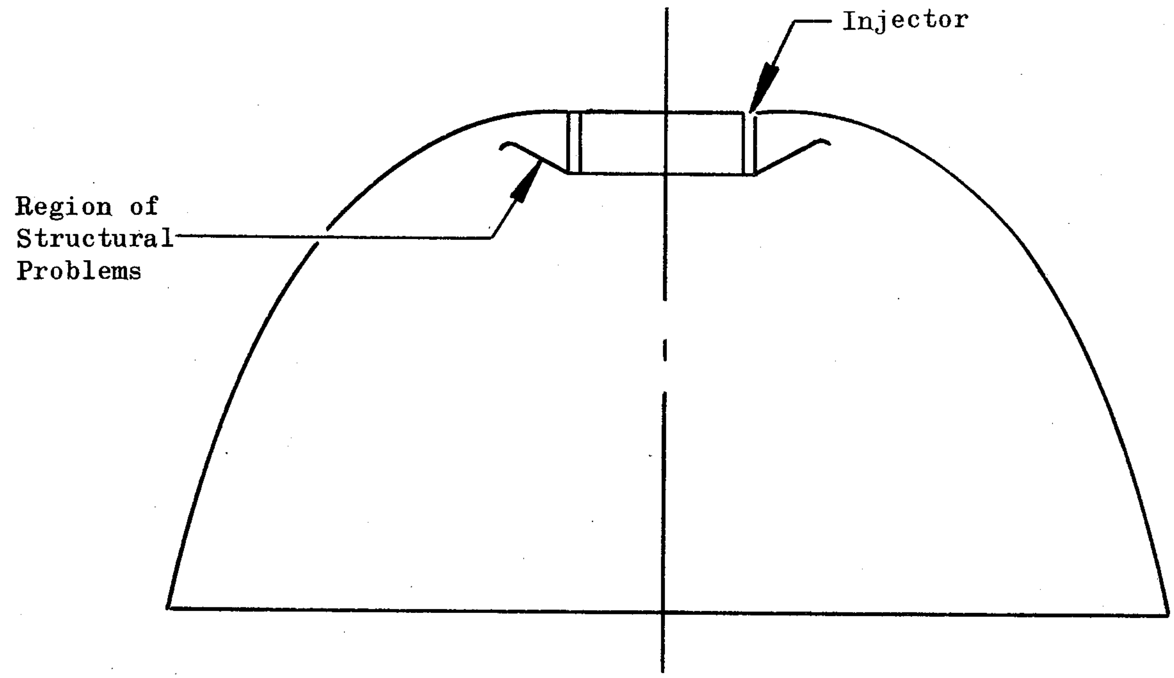

Close Tolerance at the Throat

Structural Requirements on Combustion Chamber

Design of Simple Cooling Network

Figure 1. Problem Areas of Annular Thrust Chambers

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Other combustion chamber constructions have been proposed in the past and frequently alleviate the structural and/or cooling difficulties; however, these solutions often compromise cost, reliability, or performance. The use of struts across the throat section alleviates the structural difficulty. The throat tolerance can be maintained and performance is very near that of a continuous throat. However, the cooling difficulties are not completely alleviated, and substantial weight reduction is only achieved by the inclusion of a considerable number of struts. Segmentation of the chamber or the use of multiple conventional chambers has also been considered as a solution. Designs using this approach do improve the weight. Cooling of the combustion chamber is simplified; however, nozzle manifolding and cooling between chambers requires some consideration. The performance of these configurations is also expected to be discernibly lower than continuous throat configurations.

In the quest for a solution to the combustion chamber problems, the toroidal concept was envisioned. This concept allows the coolant tube to become the basic element of the combustion chamber. The tube serves both cooling and structural requirements. Throat tolerances are maintained by swaging the tube and forming an open area between tube assemblies (Fig. 2). Verification of the concept's weight, tolerance, and cooling network advantages can be easily achieved. However, the configuration's performance capabilities and heat transfer and stress limitations could only be ascertained by a detailed investigation. The completion of this investigation by means of analytical studies, cold flow simulations, and hot firing testing was the objective of this study program.

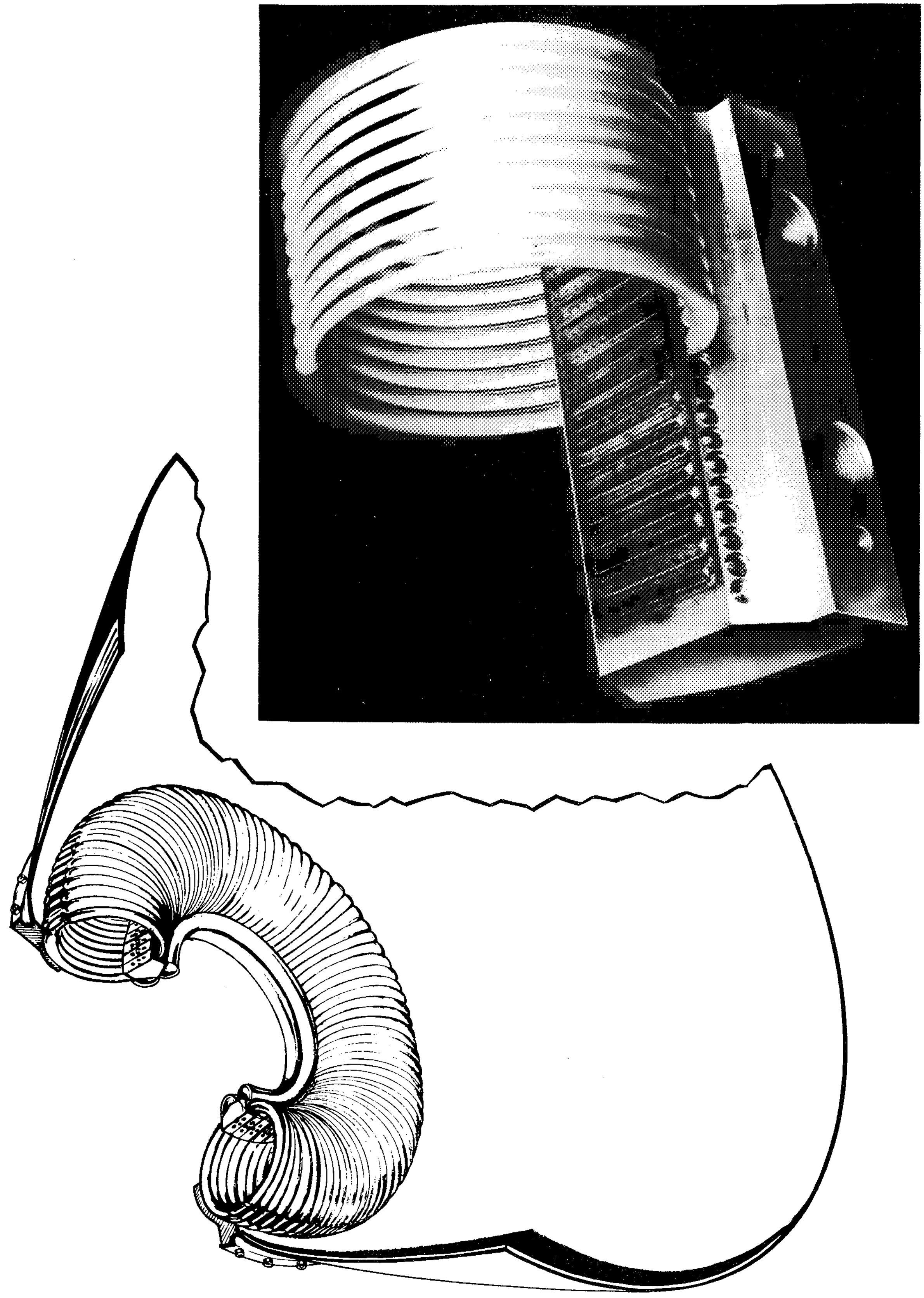

Figure 2. Toroidal Chamber

CONCEPT DESCRIPTION

The toroidal concept is illustrated in Fig. 2 and 3. A number of tapered tubes, each in the form of a hoop, are placed side by side to form an annular combustor. (The concept may be applied to any type of annular nozzle.) The name toroidal is derived from the resultant combustion chamber shape. The concept allows the coolant tube to become the basic element of the combustion chamber. The convergent-divergent section in each of the tubes results in a vertical channel between adjacent tubes (Fig. 3). This channel provides the required throat area. Each tube forms a simple coolant passage. Coolant enters at one end of the tube, circulates through the passage, is accelerated in the tapered throat region, and returns toward the injector.

Evaluation of the toroidal hoop construction technique has indicated that it is capable of providing lightweight combustion chambers. The reasons for this are evident. In all other types of combustion chamber construction, the coolant tubes are not used for any structural purposes. All structural requirements are achieved by the use of bands and other support equipment. In this chamber the coolant tubes are designed to perform a structural function as well as the normal cooling function, and the bands previously required to fulfill these structural tasks are eliminated. Thus, toroidal weights compare favorably with any configuration that does not use the coolant tubes as structural members. Weight studies have verified this conclusion.

Throat tolerance requirements are easily fulfilled by the toroidal concept. Figure 4 and 5 show a model of the toroidal combustion chamber which has been constructed. This model shows the manner in which the

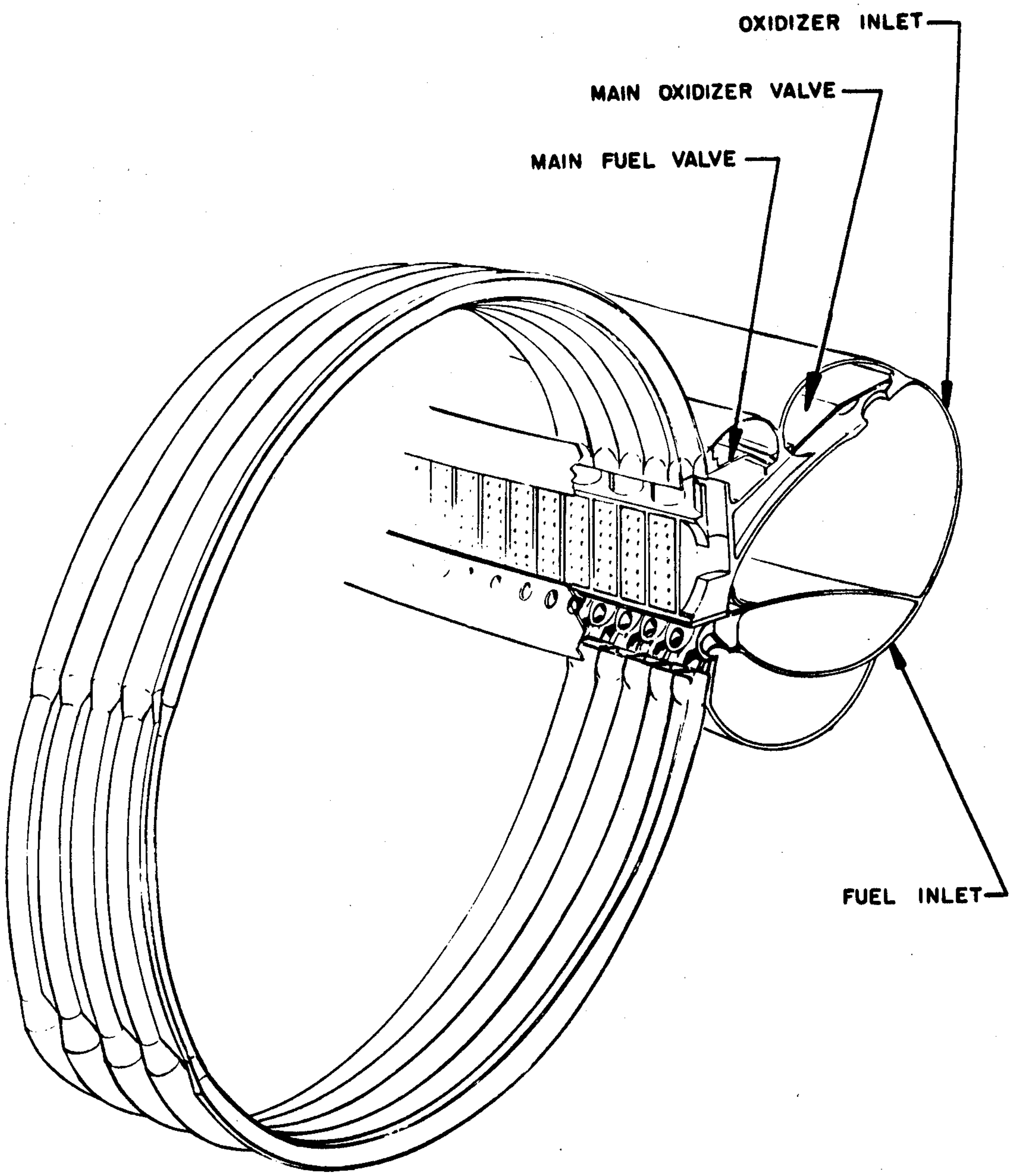

Figure 3. Toroidal Combustion Chamber

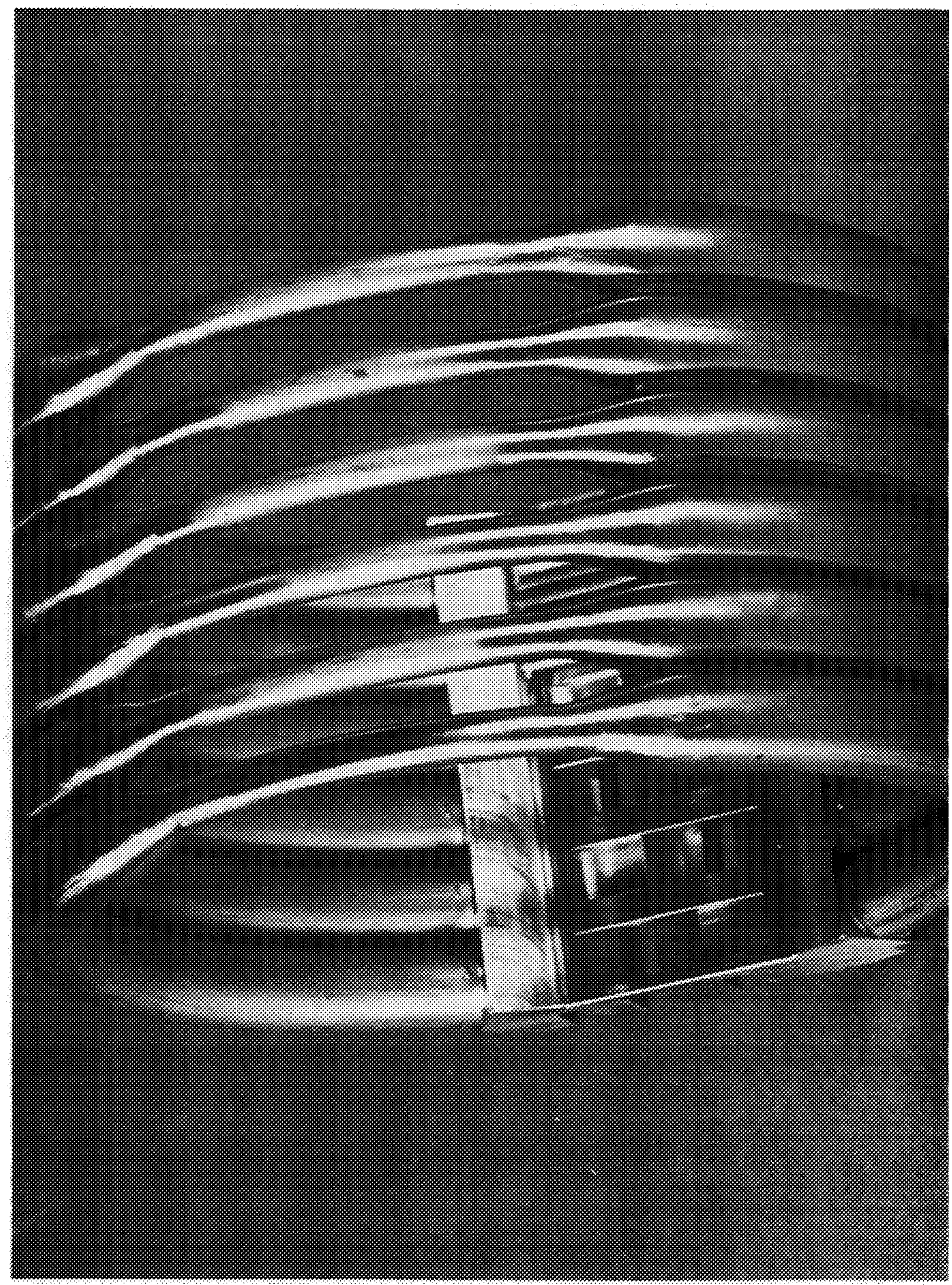

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Figure 4. Model of Toroidal Combustion Chamber

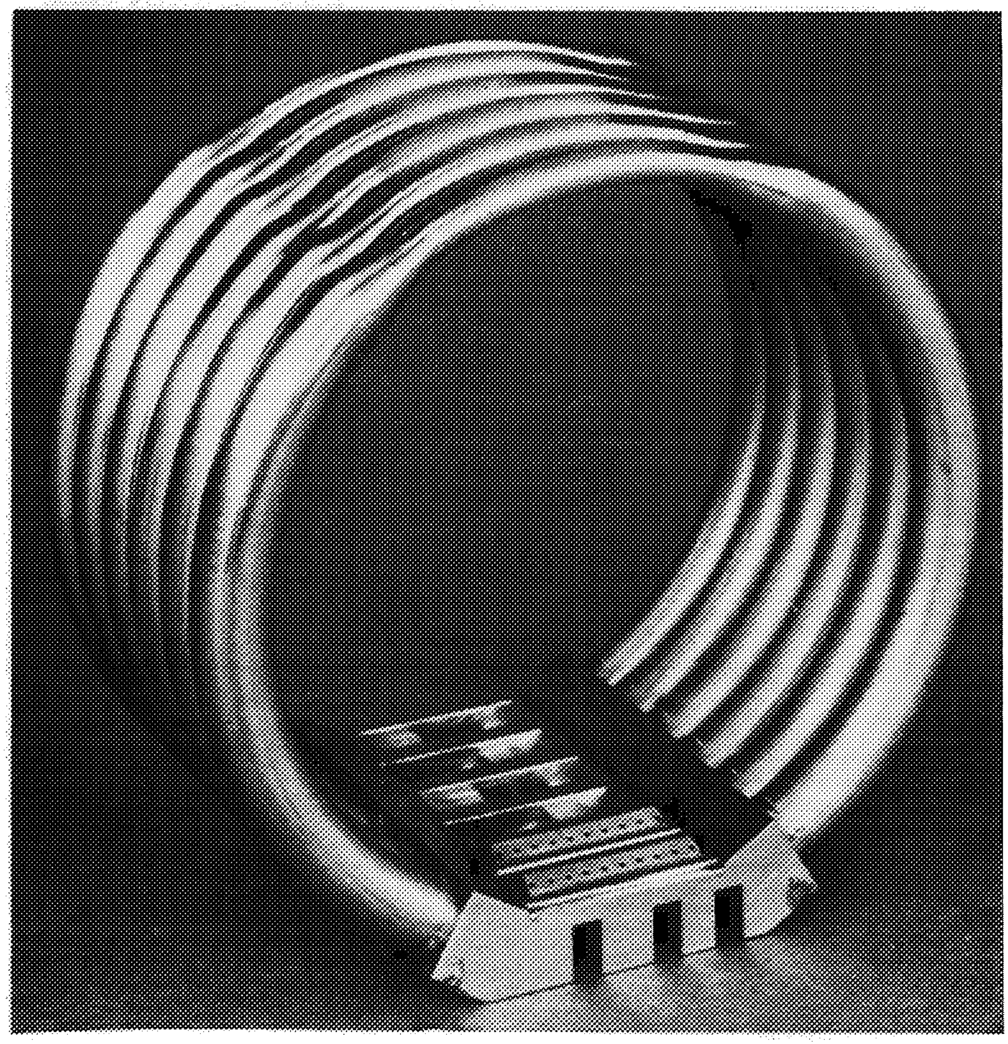

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Figure 5 . Side View of Toroidal Combustion Chamber Segment

throat is formed. Tolerance requirements for the throat are within the normal manufacturing tolerances for coolant tubes.

The use of the tube as the basic element also offers definite advantages for testing, development, and manufacturing. Several identical tubes can be rapidly assembled and test fired as a small unit. This procedure accelerates engine development and significantly reduces cost by permitting testing to be accomplished at a fraction of the final thrust level. Several of these units, baffled at each end, can then be used to form the final combustion chamber. Thus final assembly can be accomplished without requiring extensive testing at full-thrust level. The cost of the thrust chamber during production will also be reduced because mass production of identical tubes would be involved. Such a design with a single basic tube can be (1) adapted for a range of thrust levels, (2) used with a variety of nozzle types, and (3) applied in both upper stage and booster applications. In this manner, one tooling and one development program could provide engines for a very wide variety of applications.

STUDY PROGRAM

The objective of the NASA unconventional booster study program (Contract NAS 5-1026) was to determine whether new rocket engine designs can offer significant advantages over conventional systems. Results of this study indicated that there were concepts which provided gains in performance, weight, and cost. Analysis of these advanced concepts sometimes required departures from previous theoretical and design techniques. The feasibility and capabilities of such new and frequently untested ideas could only be determined by additional empirical and analytical studies.

As a result, another NASA study program (Contract NAS 8-4013) was established. The objective of this program was to evaluate the feasibility of the toroidal hoop combustion chamber construction technique (generally referred to as the toroid). The main goals of this program were to: (1) conduct aerodynamic and cold flow evaluations of the toroidal model, and examine the effects that the concept had on performance, and (2) complete analytical heat transfer and stress studies as well as hot firing demonstrations to evaluate the feasibility of the concept, and to determine operational capabilities.

Since the study was primarily divided into two sections (aerodynamics and heat transfer-stress studies) the report is similarly divided.

AERODYNAMIC STUDIES

One of the major areas of effort on the toroidal concept has been aerodynamics. By allowing the cooling tubes to span the throat region several factors which affect over-all engine performance are introduced. The major factors (flow impingement with resultant shock wave formation, expansion of the flow around the tubes, and the effect of nozzle contour) are illustrated in Fig. 6 .

To evaluate the importance of each of these factors, analytical and empirical approaches were utilized. The over-all objective of these studies was to analyze the effect of the throat inserts on the flow in the throat region, and to determine how these effects would influence over-all engine performance and design. A desired result of these studies was to provide a theory which can predict the performance of the toroidal-type configurations without testing each individual model.

To correspond with the nature of the problem, the analytical portion of the studies was divided into several parts. One phase was an investigation of the shock waves which were formed downstream of the throat tubes and their influence on performance. Another phase of the studies involved analyzing the effect of Mach numbers at the exit of the combustion chamber being greater than one (controlled expansion). The third portion of the analytical studies was the preparation of the toroidal chamber nozzle design technique.

Cold flow testing of the toroidal configurations was conducted in conjunction with the analytical aerodynamics studies. These tests not only provide visual and physical data to evaluate any analytical predictions

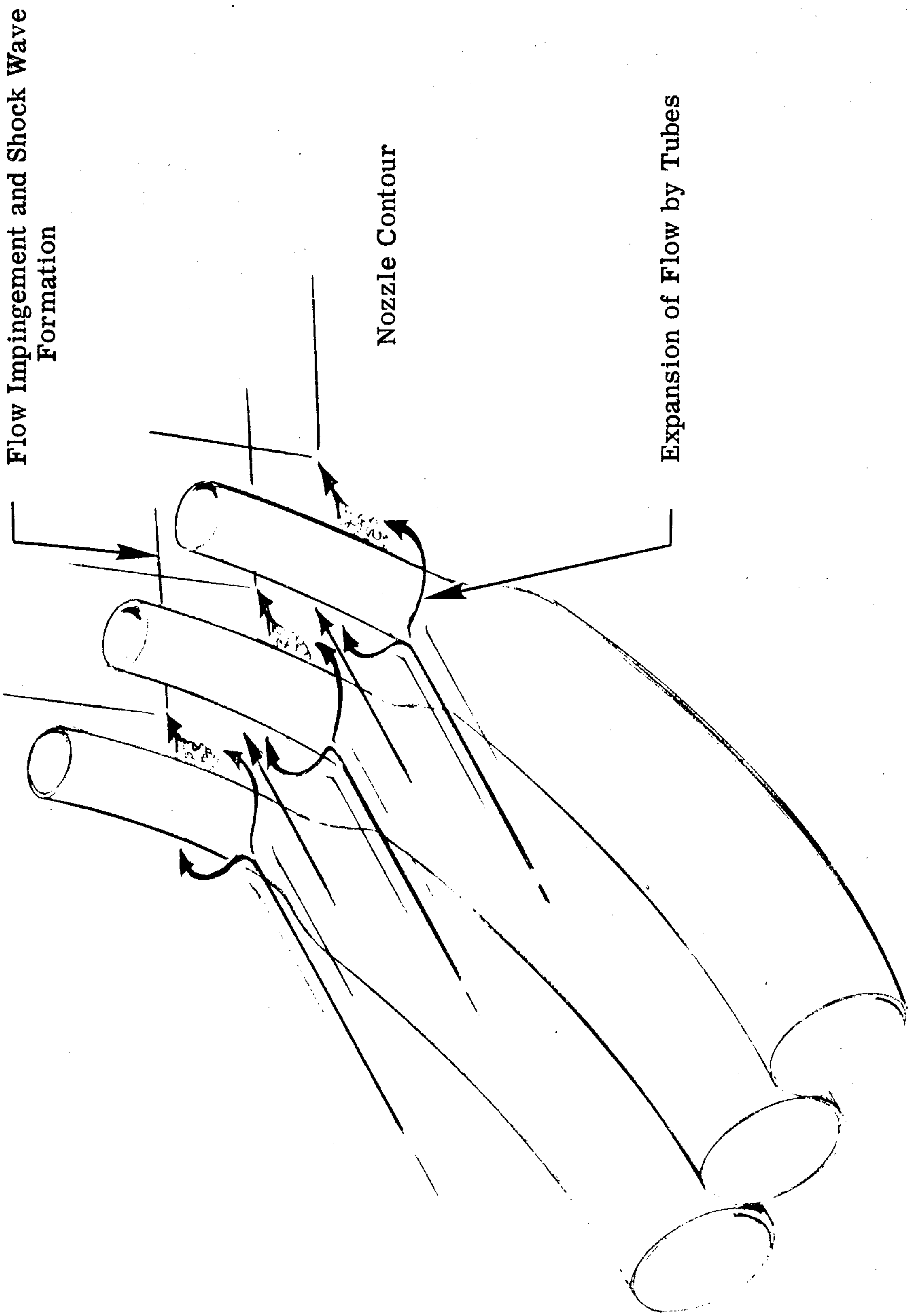

Figure 6. Factors Affecting Performance

of toroidal performance, but when necessary, also provide a basis for the establishment of empirical constants.

INFLUENCE OF STAGNATION PRESSURE LOSSES ON PERFORMANCE

During the operation of the toroidal chamber, stagnation pressure losses are incurred due to skin friction and the shock waves resulting from flow impingement past the tubes. A rapid analysis of the effect of skin friction indicates that, although the surface area of the tubes is considerable, the boundary layer is quite thin and the frictional losses are negligible. However, discernible stagnation pressure losses will occur when shock waves are formed downstream of the tube configurations. The magnitude of these stagnation losses will be influenced by the cross-sectional shape of the tubes and their spacing. At one end of the performance spectrum is the infinitely thin tube, or the tube with the aerodynamically shaped cross section. Such configurations would have virtually no loss in total pressure, and would perform the same as a comparable continuous throat configuration. At the other end of the performance spectrum are the circular cross-sectioned throat tubes. Such tube configurations simplify construction and cooling of the chamber, but introduce stagnation pressure losses due to the shocks behind the tube.

To determine analytically the extent of the stagnation pressure losses and their effect on performance, it is necessary to predict the flow properties up to and through the shocks. Thus the analysis can be divided into five basic regions: (1) description of the transonic flow field, (2) evaluation of tube base pressures, (3) prediction of flow separation from the tube and the impingement angle of the shocks, (4) calculation of the stagnation pressure losses, and (5) relation of stagnation pressure losses to performance. The nomenclature illustrated in Fig. 7 is convenient for interpretation of study results.

Transonic Flow

Before any conclusions can be made relative to flow in the throat region, it is imperative that the nature of the sonic line be determined. The geometry of the sonic line is dependent upon tube geometry, and for various reasons is far from the straight line (assumed in one-dimensional gas dynamics) which represents geometrical throat area. There have been many classical approaches computing the geometry of this line. The best known is perhaps the Sauer parabolic approximation. However, this method does not give sufficiently accurate predictions for the curvature of the tube walls encountered in the toroidal configuration. Therefore, a method has been formulated as a replacement for the Sauer approximation. This method (developed by Dr. W. R. Seugling of Rocketdyne) attempts solution of the nonlinear formulations describing the transonic flow field by a power series solution. Throughout the study, flow properties in the throat region have been based on the Seugling technique. A comparison of this technique with experimental data has yielded excellent correlation.

Base Pressure Theory

Experimental data have indicated the tube wall pressure continually decreases from the stagnation point to a point approximately 120 degrees around the tube. From this point to the rear of the tube approximately

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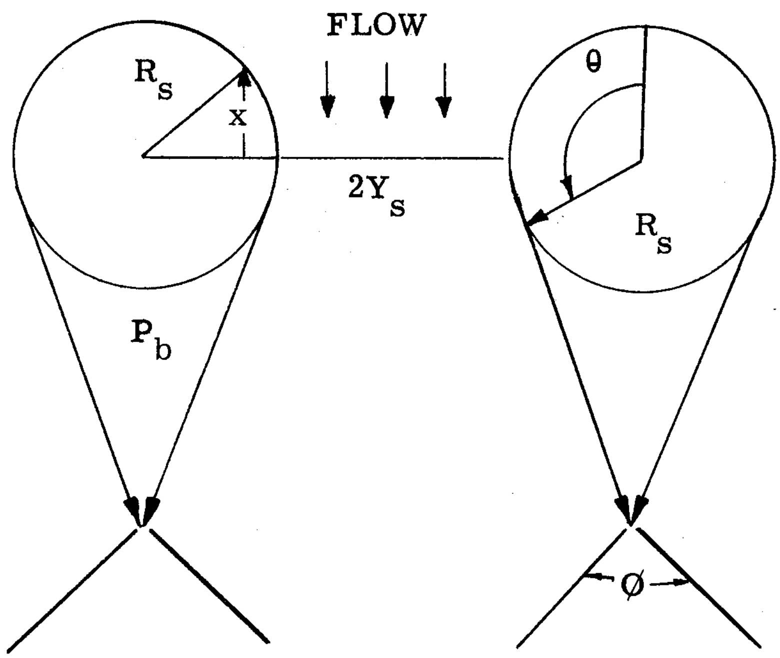

Figure 7. Nomenclature

constant wall pressure is maintained. This region is one in which the main flow has separated from the tube, and the pressure in this region is referred to as tube base pressure (P_b). Knowledge of the pressure in this region is necessary before it can be accurately predicted where the flow will separate from the tube, the angle at which it will expand, and the types of shocks that will be formed. In attempts to predict the base pressures, several theoretical models for which base pressure had been evaluated were considered for their applicability. A two-dimensional model which underwent an abrupt change in area was used and yielded some correlation with experimental data. Even closer approximations of the experimental values may be achieved by using a two-dimensional model which introduces curvature in the region where the area is increased. This model would closely simulate the actual conditions encountered in the toroidal chamber. Since analysis with this model would require lengthy and cumbersome calculations, empirical values were used for subsequent calculations.

Flow Separation and Shock Formation

With knowledge of the sonic line and base pressure conditions, it was possible to predict the point where the flow separates from the tube and impingement angle of the shocks. This was done by assuming Prandtl-Meyer expansion of the flow along the tube into a region of known base pressure. Separation points (θ) for various tube spacings were thus predicted. Subsequent to separating from the tubes, the flow will continue to expand and meet the flow expanding from the other side of the tube.

The effect of this shock on stagnation pressure is a direct function of the impingement angle. This angle (ϕ) was calculated. Both the separation point and impingement angle were compared to empirical data. Analytical and empirical data are shown in Fig. 8 . A close correlation was found.

Stagnation Pressure Losses

With knowledge of the shock impingement angle and the flow properties prior to the shock, it was possible to calculate the stagnation pressure losses across the first shock and, by similar methods, the stagnation pressure losses across subsequent shock formations. The results of these calculations are shown in Table 1 . For one tube spacing ($R_s/R_s + Y_s = 0.5$), the predicted stangation pressure loss across the first shock is slightly less than 5 percent; the loss across the second shock is less than 1/2 percent. Since losses across subsequent shocks would be even smaller, they were ignored. The total loss for this spacing is approximately 5-percent total pressure. For other spacings shown on the table, losses are approximately 10 and 20 percent, respectively.

Effect on Performance

Generally, the losses in specific impulse are considerably less than those in stagnation pressure. The relationship was derived and is presented in the aerodynamic section of the report. The results are indicated in Fig. 9 for an altitude compensating nozzle with a 20:1 expansion ratio. This figure indicates C_τ, which is the relationship of actual performance to ideal performance for a given altitude, vs pressure ratio.

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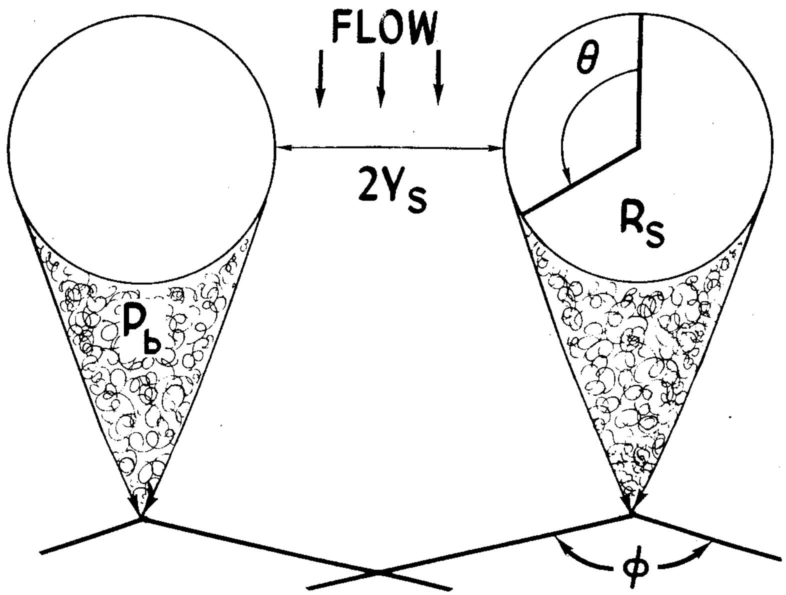

RADIUS RATIO $\left(\frac{R_S}{R_S + Y_S}\right)$	PREDICTED SEPARATION POINT, θ	MEASURED SEPARATION POINT, θ	PREDICTED IMPINGEMENT ANGLE, ϕ	MEASURED IMPINGEMENT ANGLE, ϕ
.500	112.3°	115°	58.4°	60°
.583	115.6°	117°	58.8°	60°
.667	120.4°	125°	61.2°	63°

Figure 8. Prediction of Separation Point and Impingement Angle

TABLE 1

EFFECT OF TUBE SPACING ON TOTAL PRESSURE

$\left(\frac{D_t}{D_o} = \frac{R_s}{R_s + Y_s}\right)$	$\frac{P_{o_{s_1}}}{P_{o_1}}$	$\frac{P_{o_{s_2}}}{P_{o_{s_1}}}$	$\frac{P_{o_{s_2}}}{P_{o_1}}$
0.500	0.9531	0.9999	0.953
0.583	0.9026	0.9997	0.902
0.667	0.7993	0.9982	0.798

where

P_{o_1} is the total pressure before the first shock

$P_{o_{s_1}}$ is the total pressure between first and second

$P_{o_{s_2}}$ is the total pressure after the second shock

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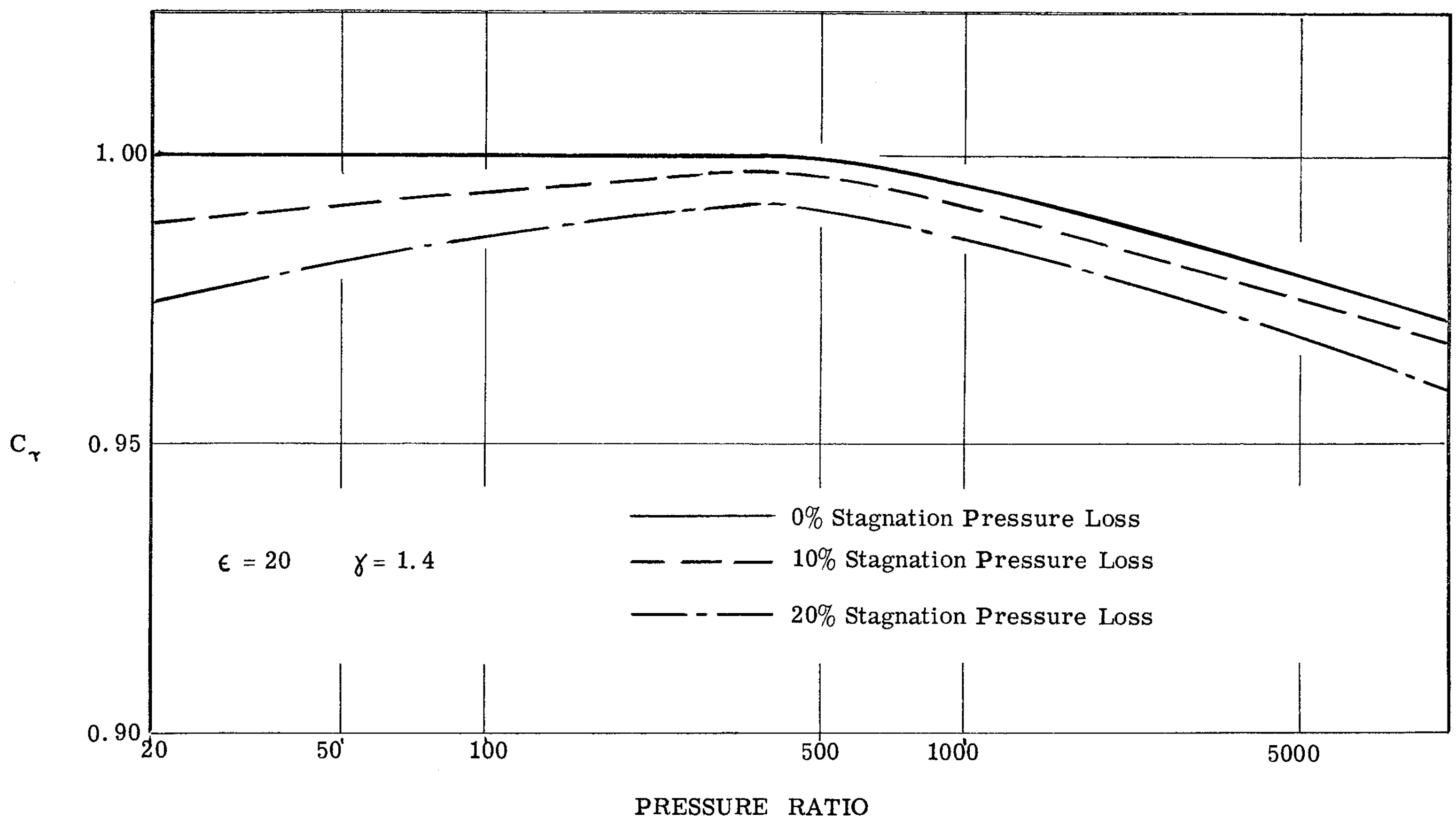

Figure 9. Effect of Stagnation Pressure Losses on Performance

The solid line indicates performance of a 20:1 altitude compensating nozzle with 0 stagnation losses. The nozzle performs as an ideal nozzle up to a pressure ratio of 382, at which point the nozzle is fully expanded. Also shown on this figure are lines representing 10- and 20-percent stagnation pressure losses. For a typical booster application, a 20-percent stagnation pressure loss would correspond to approximately a 1-percent performance loss at all altitudes. A 5-percent stagnation pressure loss ($R/(R_s + Y_s) = 0.5$) would correspond to performance loss of less than one-half of 1 percent at all altitudes.

The effect of shock on performance may be summarized. Approximately a 1-percent loss is predicted for circular tubes with unfavorable spacing; less than half of 1 percent is predicted for most common spacings with circular tubes. Even smaller losses would occur if tubes with contoured configurations were used.

CONTROLLED EXPANSION

A typical cross section of three tubes is shown in Fig. 10. Here, it is possible to visualize some of the factors that have been discussed in previous paragraphs: the separation of the flow from the tubes, formation of shocks behind the tubes, the region of base pressure, and expansion of the flow as it passes from the throat to the downstream side of the tube. This effect is referred to as controlled initial expansion, and it has several ramifications on over-all nozzle performance. The effects of controlled initial expansion are illustrated in Fig. 11 . Here a cross section

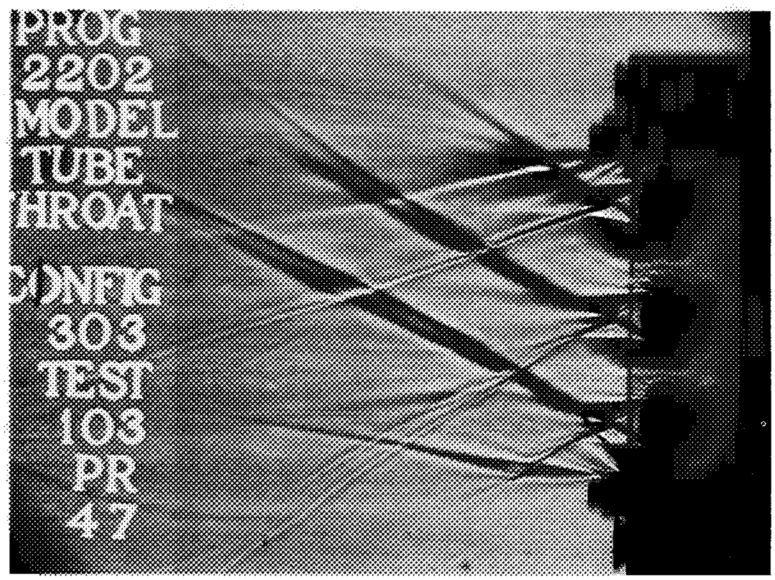

Figure 10. Controlled Expansion

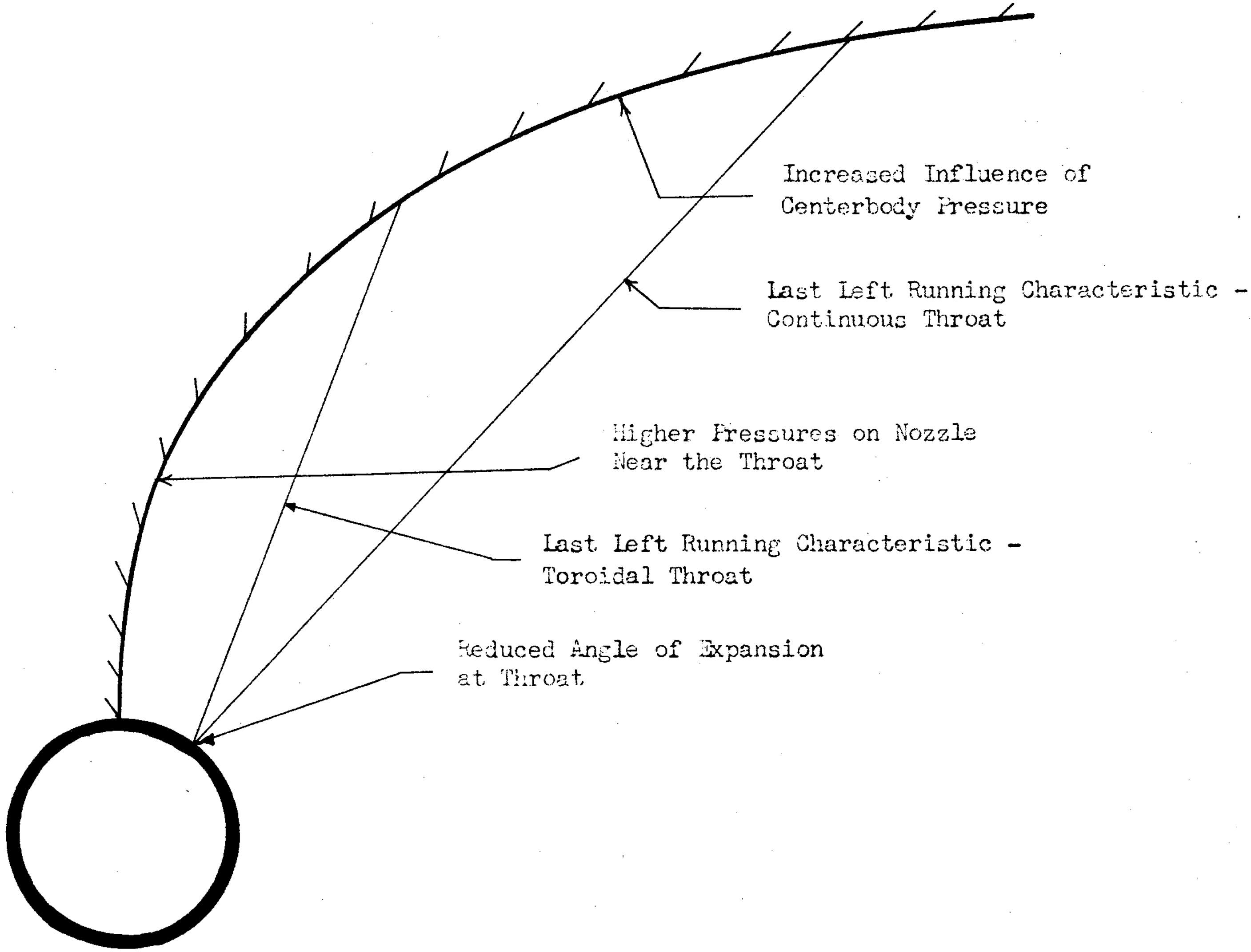

Figure 11. Effects of Controlled Expansion

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of a nozzle and a combustion chamber are shown. After flow leaves the combustion chamber, the amount of expansion at the throat is a function of the centerbody pressure and the Mach number of the combustion gases. If a comparison is made between a continuous throat configuration and a toroidal configuration (assuming centerbody and combustion chamber pressures to be equal) the initial expansion of gases at the throat with a continuous configuration will be considerably greater than for the toroidal configuration. This is a result of the higher Mach number in the throat region of the toroid.

The angle of this initial expansion dictates the position of the last left-running characteristic line. To the left of this line, centerbody pressure will not enforce wall pressure. To the right of this line, centerbody pressure will influence wall pressure. Thus, the second effect of the controlled initial expansion in the toroidal configuration is to increase the influence of centerbody pressure on the nozzle. This is particularly important at low-altitude operation, and will increase performance under these conditions. However, it will slightly decrease performance at high pressure ratios. In addition, a controlled initial expansion will tend to produce higher wall pressures on the nozzle near the throat. This factor is beneficial to performance at all altitudes, because it increases the axial thrust component of the nozzle configuration.

These factors can be more vividly illustrated by the flow fields and pressure profiles calculated by the method of characteristics for a continuous throat and a toroidal-type configuration at a pressure ratio of 20 (Fig. 12 and 13). The flow fields for the continuous and the aerodynamic configurations are shown in Fig. 12. Comparison of the two

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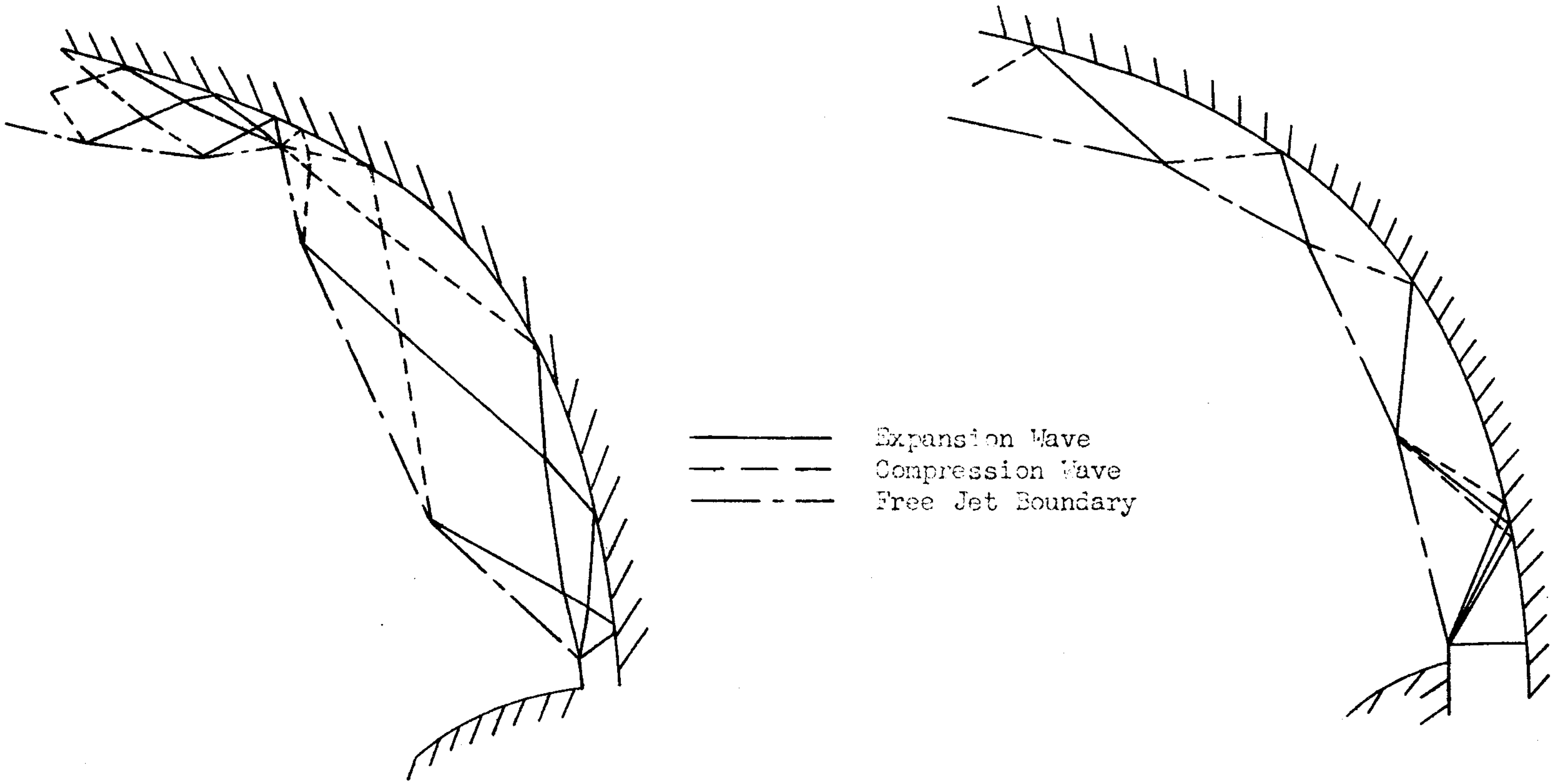

Continuous Throat

Toroidal Throat

Figure 12. Flow Field Calculated by Method of Characteristics
(Pressure Ratio = 20)

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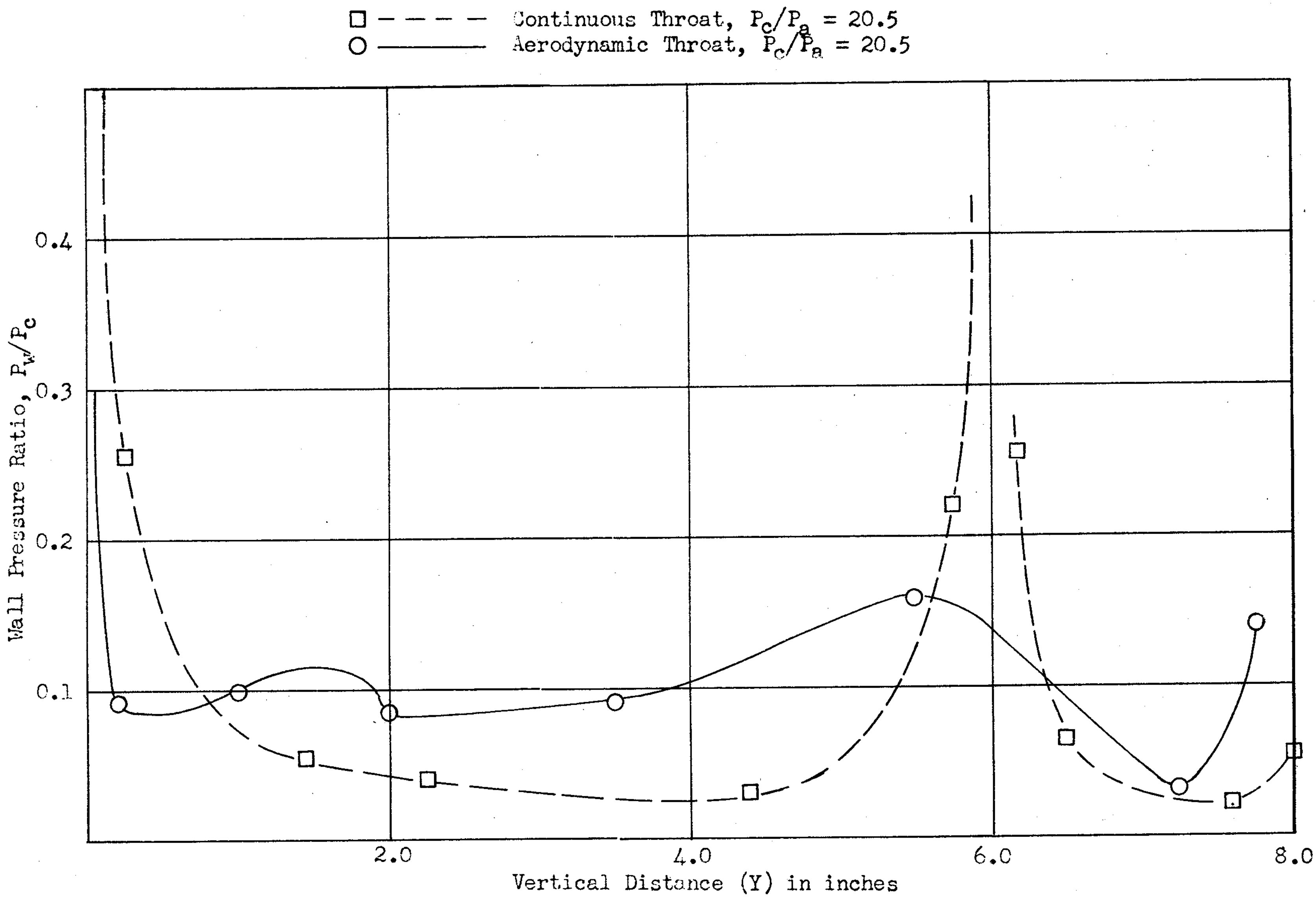

Figure 13. Theoretical Nozzle Wall Pressure Profile

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flow fields immediately indicates that the expansion at the throat is considerably less for the toroidal configuration. The resultant effects on the pressure profile are shown in Fig. 13. Here, the wall pressure in the first half of the nozzle is considerably greater with the toroidal configuration. On the lower portion of the nozzle, a distinct pressure rise occurs for both configurations (recompression). However, this pressure rise occurs farther downstream for the continuous configuration. These figures thus illustrate the three major effects of controlled initial expansion. These effects are, altered flow expansion at the throat, higher pressure in the first portion of the nozzle, and increased influence of ambient conditions. The over-all effect of controlled initial expansion on performance is to provide substantial increases in performance at low-pressure ratios, and to slightly decrease the performance at very high-pressure ratios.

NOZZLE EFFECTS

During this program, studies were made to develop the theory which would aid in the design of optimum nozzles for the toroidal configuration. Such a theory should take into account throat flow characteristics such as the effect of shocks, the curvature of the throat, and the higher exit Mach numbers at the throat due to controlled expansion. By considering these factors and using the throat exit properties as an input line, a kernel flow field may be developed. With this kernel flow field, it is possible to select the control surface and evaluate various contours and complete thrust maps to determine appropriate nozzle design criteria for toroidal configurations. During this program the theory and procedures for accomplishing these goals have been completed. These procedures are discussed in the main text of the report. However, calculations for any single nozzle are lengthy and therefore not suitable for hand calculation. In the future these procedures will be programmed and solved by machine calculation.

SUMMARY OF ANALYTICAL AERODYNAMIC PERFORMANCE PREDICTIONS

The results of the analytical studies may be used to give a qualitative picture of what effect the toroidal configuration will have on over-all nozzle performance. Such a picture is shown in Fig. 14. Here, a typical performance curve for the continuous throat is shown. Superimposed on this is the effect of the controlled expansion. Controlled expansion results in a large gain in performance at low-pressure ratios (low altitudes) and a slight loss in performance at very high-pressure ratios (high altitudes). Controlled expansion is inherent in the toroidal nozzle; however, it should be noted that a continuous throat with an interior shroud or double wall could also achieve a similar effect.

In addition to the effect of controlled expansion, the effect of the shock losses in the throat region must be considered. This has been shown to be a function of the spacing and the tube cross sections. However, for a typical circular tube spacing, a loss somewhat less than one-half of 1-percent in performance will occur at all pressure ratios. This effect

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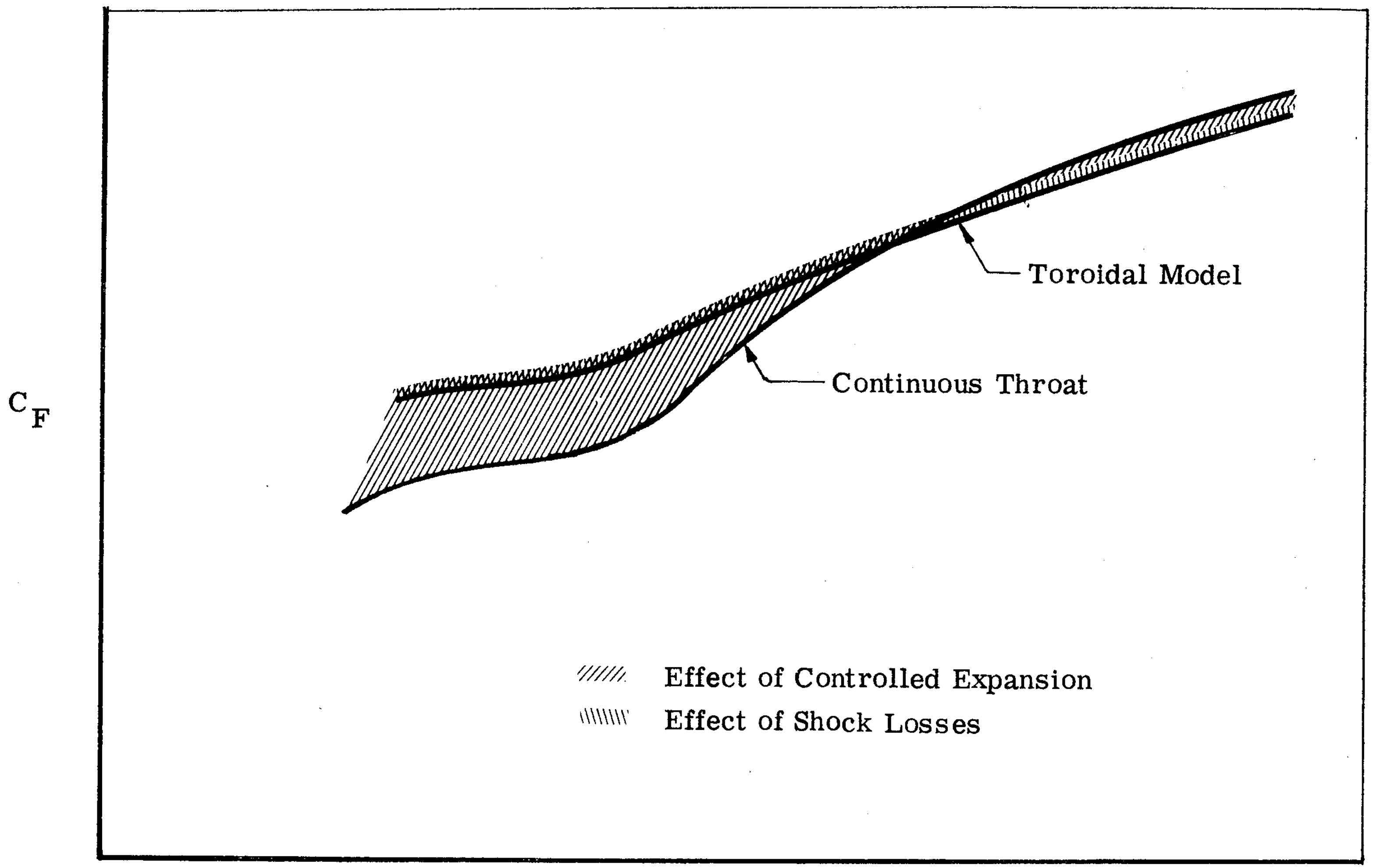

Figure 14 . Typical C_F Curves, Pressure Ratio (P_c/P_a)

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is also shown in Fig. 14 . Thus, the over-all performance of a toroidal model appears to be greater than the continuous throat for low-pressure ratios and slightly less than the continuous throat under high-pressure ratio (high altitude) conditions. This qualitative analytical picture may now be compared with the results of wind tunnel testing.

COLD FLOW PROGRAM

The cold flow program consisted of a series of wind tunnel tests to obtain information about: (1) changes in nozzle performance resulting from non-isentropic flow downstream of the throat, (2) thrust developed through expansion of gases in the nozzle, (3) flow patterns in the vicinity of the throat and in the nozzle, (4) base pressures on the downstream side of the throat tubes, (5) pressure distribution on throat tubes and nozzle walls, and (6) the effect in the variation in the pressure ratio on all these items. To accomplish these objectives a two-dimensional model was designed and built. The model (Fig. 15) incorporates a replaceable throat section which allows for the use of various tube cross sections, an expansion shroud (nozzle) to expand the gases, and two transparent side plates to allow observation of the flow. Recorded data included pressure, flow, thrust measurements, and Schlieren photography. Four basic throat configurations were evaluated: (1) a throat formed by a continuous rectangular opening, (2) a throat formed by spaces between struts of circular cross section, (3) throat formed by struts of streamlined cross section, and (4) throat formed by struts of a semistreamlined cross section. These configurations are referred to throughout the text respectively as continuous, circular, aerodynamic, and semiaerodynamic throat configurations.

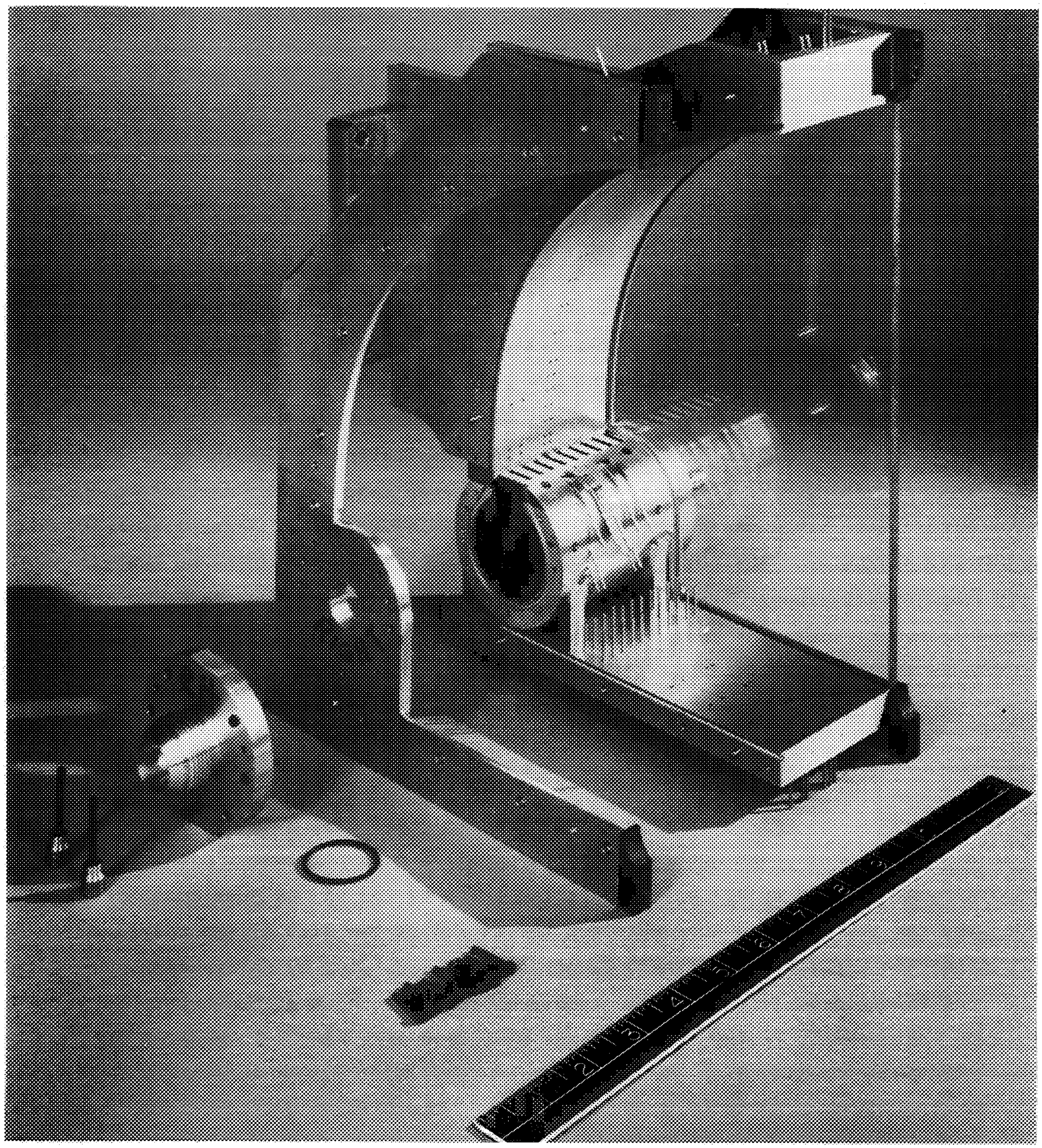

Figure 15. Wind Tunnel Model With Shroud

Flow Field and Pressure Measurements

Throughout the test program, empirical data were found to have close correlation with analytical predictions. The Schlieren photographs shown in Frontispieces A and B illustrate some areas of agreement. Frontispiece A visualizes the flow field for a continuous throat configuration at a low-pressure ratio. The flow field of a toroidal configuration at a comparable pressure ratio is illustrated in Frontispiece B. There is extremely close correspondence between the photographed flow fields and the flow fields calculated by the methods of characteristics. It may be observed that the sustained angle of the flow leaving at the throat region in the continuous model is considerably greater than for the toroidal configuration. This was previously discussed as an effect of controlled initial expansion. The relationship between the Schlieren photographs and the nozzle wall pressure profiles can be seen in Fig. 16 and 17. These figures validate the analytical prediction of increased wall pressures near the throat of the toroidal configuration. Figure 16 and 17 also show the values of wall pressure calculated by analytical procedures.

The occurrence of recompression can be observed for the toroidal and continuous throat configurations (Frontispieces A and B). An orange background color is used for each of these Schlieren photographs. Expansion is indicated by colors approaching the infrared end of the spectrum; thus, the red and deep red hues near the throat and at the exit of the nozzle indicate areas of expansion. Compression is indicated by colors approaching the untraviolet end of the spectrum; thus, increasing compression will be indicated by yellow, green, light blue, and dark blue. In each of the

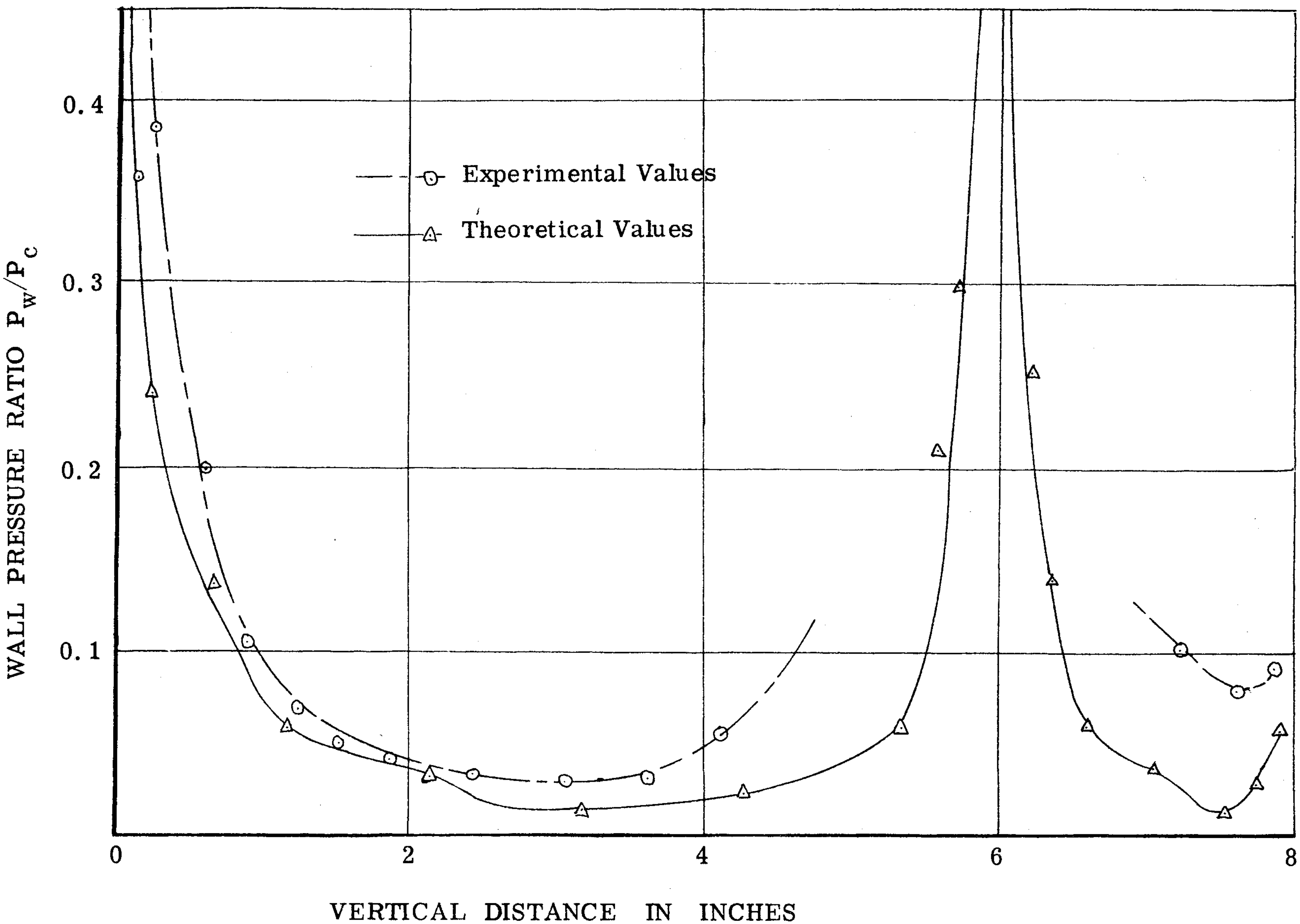

Figure 16. Nozzle Wall Pressure Profile, Continuous Throat

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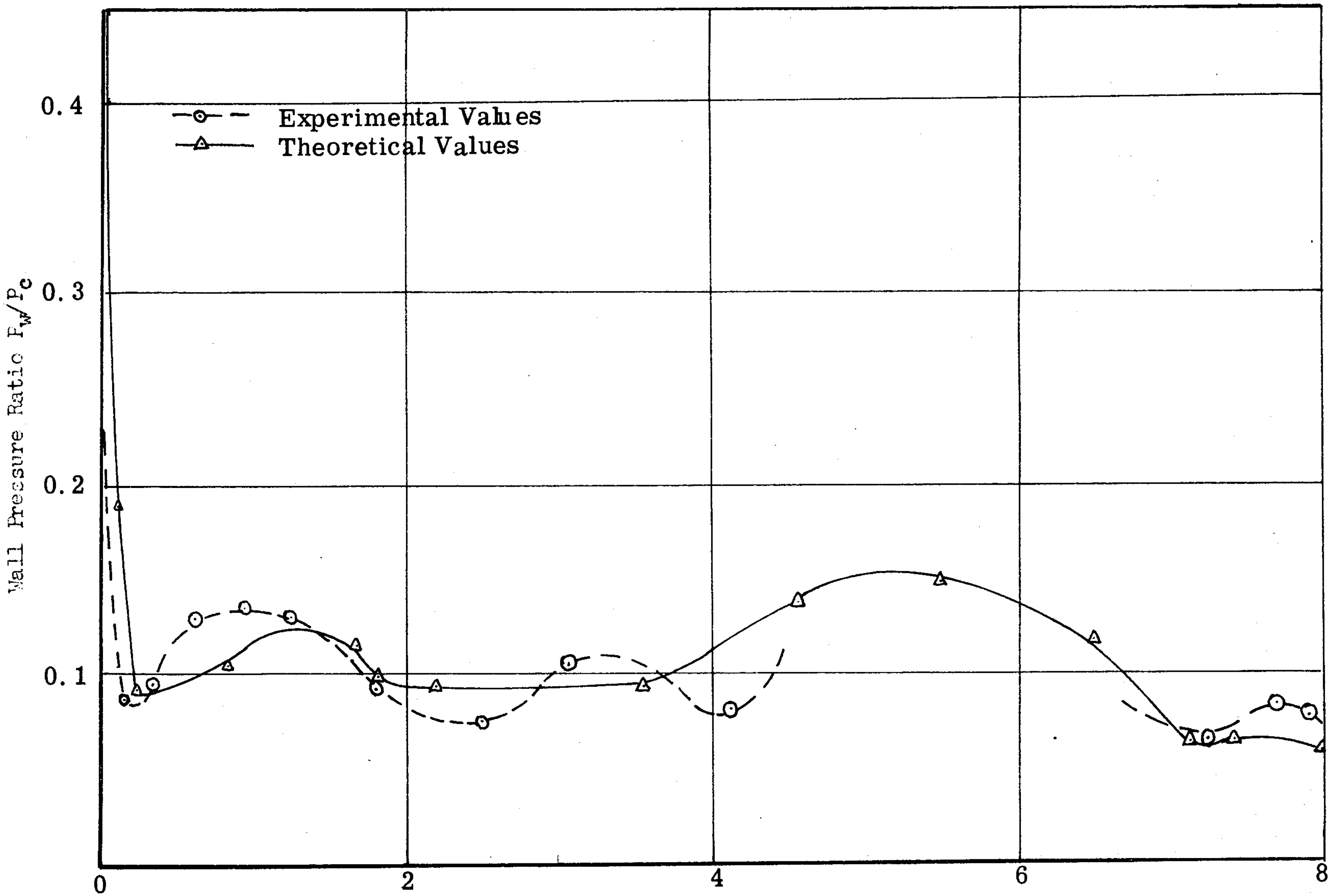

Figure 17. Nozzle Wall Pressure Profile, Aerodynamic Throat

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photographs an area of heavy recompression will be noted. The locations of the recompression regions were predicted analytically. Since controlled initial expansion increases the influence of base pressure on the nozzle, recompression for the toroid would occur nearer the throat (at any given pressure ratio) and favorably affect performance over a larger range of pressure ratios. For the continuous throat configuration (Frontispiece A), this heavy recompression occurs approximately two-thirds down the nozzle; for the toroidal configuration (Frontispiece B) the deep blue region (heavy recompression) occurs approximately halfway down the nozzle.

Performance Data

Comparative performance of a continuous throat model and the circular-pin throat toroidal model is indicated in Fig. 18 . The results of the wind tunnel tests have indicated that the circular-pin model will greatly improve performance characteristics at low-pressure ratios and slightly decrease performance at high-pressure ratios. These results agree with qualitative analytical results shown in Fig. 14.

The results of testing toroidal configurations with aerodynamic and semi-aerodynamic throats are shown in Fig. 19 . As expected, the aerodynamic throat configuration achieves high performance over a wide range of pressure ratios. The semiaerodynamic throat achieved performance comparable to the circular-pin throat over most operational conditions. Although an increase in performance can be achieved by the use of aerodynamic throat configurations, at most pressure ratios the cross section of the tube has only a small effect on performance. This factor has led to the recommendation of the circular pin tubes since these tubes are more economical, simpler to manufacture, and easier to cool.

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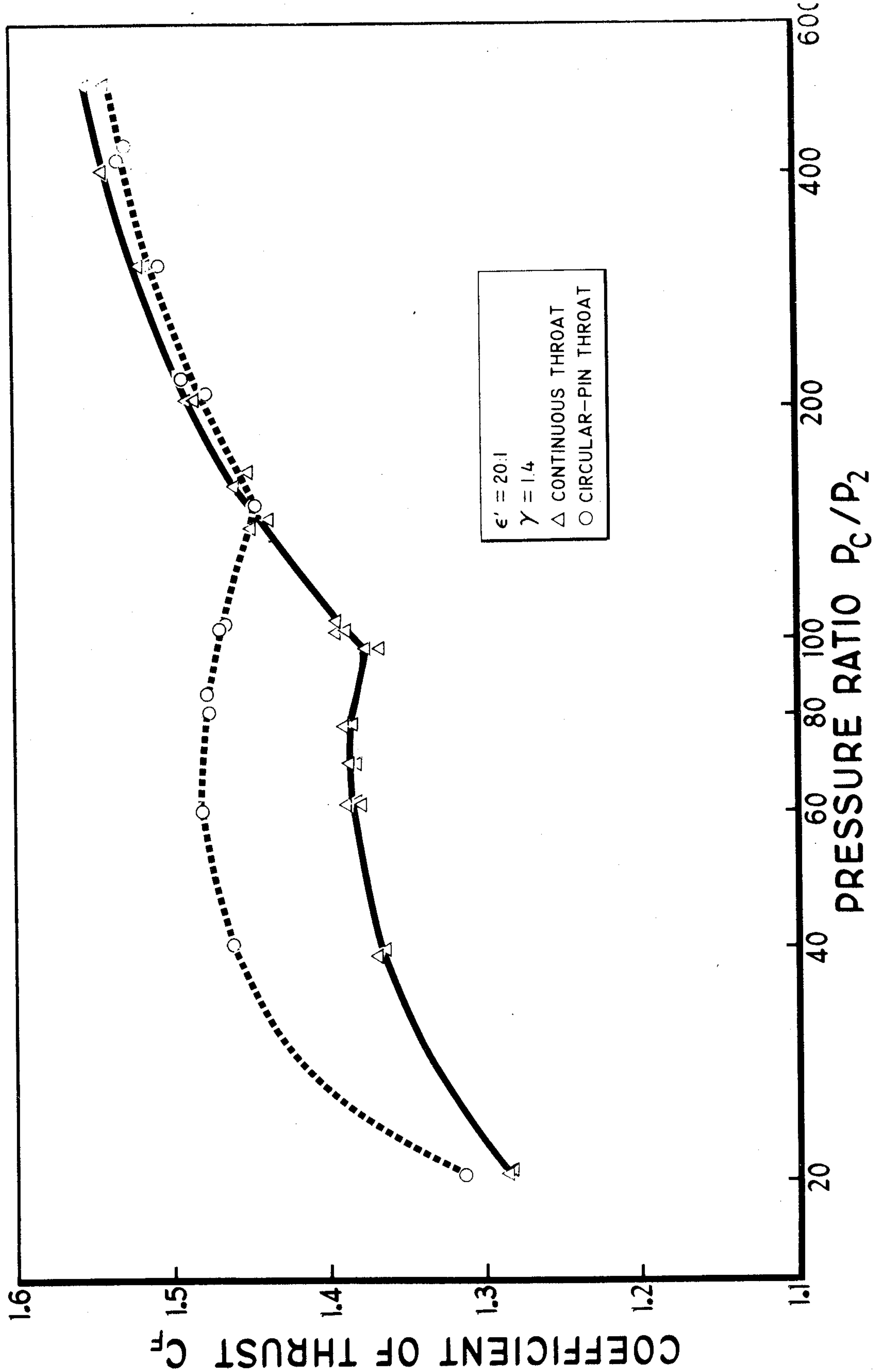

Figure 18. C_F vs Pressure Ratio

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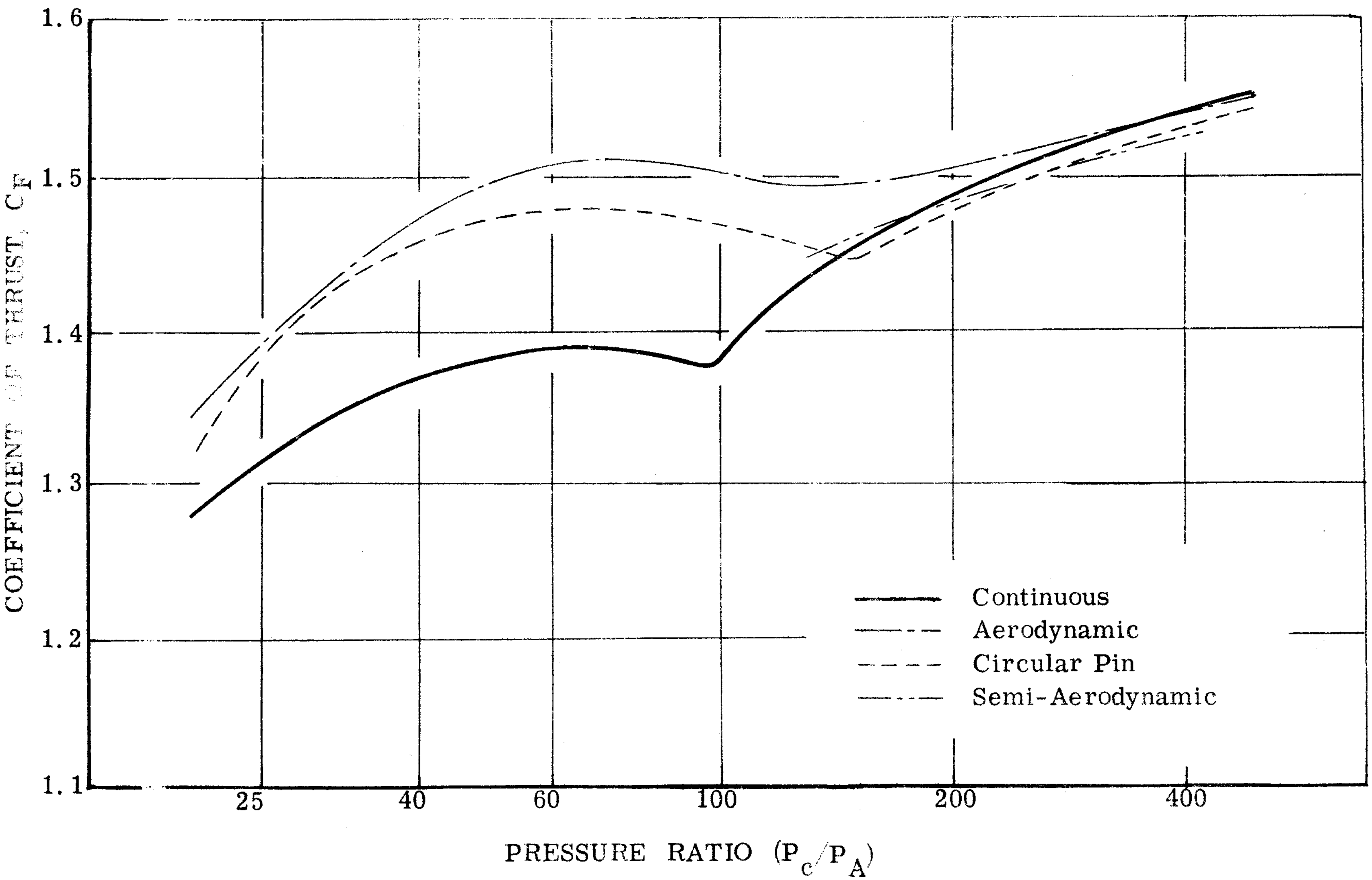

Figure 19. Performance of Cold Flow Models

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AERODYNAMIC STUDY CONCLUSIONS

A few of the major conclusions which can be drawn from the aerodynamic studies are listed below:

1. The major aspects of the toroidal aerodynamics can be predicted analytically. Performance and flow field variations due to such parameters as tube spacing, tube cross section, and nozzle contour, are all amenable to theoretical solutions.

2. There was close agreement between experimental data and theory. This was evidenced in comparison of flow fields, pressure profiles, and performance calculations.

3. The tube cross section has a small effect on performance. This factor leads to the recommendation of circular cross-section tubes since these tubes are more economical, simpler to manufacture, and easier to cool.

4. There is a small loss in performance due to the shocks formed downstream of the tubes. This loss occurs at all pressure ratios. Calculations have shown that for common tube spacings this loss will be less than 0.5 percent.

5. Improved performance at low-pressure ratios is achieved by controlled initial expansion. These gains are inherent with toroidal configurations; however they can also be achieved in continuous throat models by utilizing a double-wall expansion shroud.

HEAT TRANSFER AND STRESS

Since the cooling tubes in the toroidal chamber also fulfill structural requirements, the stress and heat transfer calculations are closely related. Therefore, careful consideration must be given to the tube design at all operating conditions. The objectives of this section of the report were to evaluate the heat transfer and stress requirements for the toroidal chamber and establish the operational capabilities of the concept. This was done by: (1) deriving an analytical model of the heat transfer and stress considerations for the toroidal concept; (2) conducting parametric studies of toroidal chambers using both oxygen/hydrogen and oxygen/RP propellants with various tube materials, various geometries, and various types of cooling; and (3) improving the analytical description of the combusion chamber and throat-region heat-transfer coefficients by the use of hot firing and cold flow data. The work completed in these areas is summarized on subsequent pages.

GEOMETRICAL CONSIDERATIONS

Toroidal combustion chamber design considerations, such as size and weight, are influenced by five independent geometrical variables: (1) combustion chamber radius, (2) tube diameter, (3) tube contraction ratio, (4) the angular opening of the throat (swaged portion of the tube), and (5) the tube contraction ratio. These geometrical variables also have an important influence on the tube stress and heat transfer requirements. It was desirable to develop equations describing the toroidal chamber to aid in evaluating the numerous possible geometric combinations and the influence of geometry on heat transfer and stress. These equations and some simple results are indicated in the main text.

PARAMETRIC STRESS STUDIES

One of the most critical considerations affecting toroidal chamber feasibility is the stress level required of the materials. The stress analysis of the toroidal combustion chamber was based on three general loading conditions: (1) pressure stresses due to the chamber pressure, (2) pressure stresses due to the static pressure in the coolant tubes, and (3) thermal stresses which result from heat fluxes through the tube walls. Both elastic and plastic conditions were considered. The derivation of the stress equations and the analytical model is presented in the main text of the report.

For a given tube material and combustion chamber geometry, minimum allowable tube wall thickness will be established by pressure stress considerations. This minimum thickness represents the least amount of material required to maintain structural integrity without exceeding the yield stress. Similarly, a maximum tube thickness is established by the thermal stress requirements. This thickness is a function of the heat flux. By simultaneously solving for these two conditions, pressure stress and thermal stress, a maximum allowable heat flux can be calculated for each operational chamber pressure (assuming a chamber geometry and tube material). Such a function (for Inconel-X with a specified chamber geometry) is indicated in Fig. 20 . It can be seen that at low chamber pressures extremely high heat fluxes may be sustained, because thin tube walls can fulfill pressure stress requirements. However, as chamber pressure increases, pressure stress and wall thickness also increase; therefore, tube heat flux capabilities are reduced.

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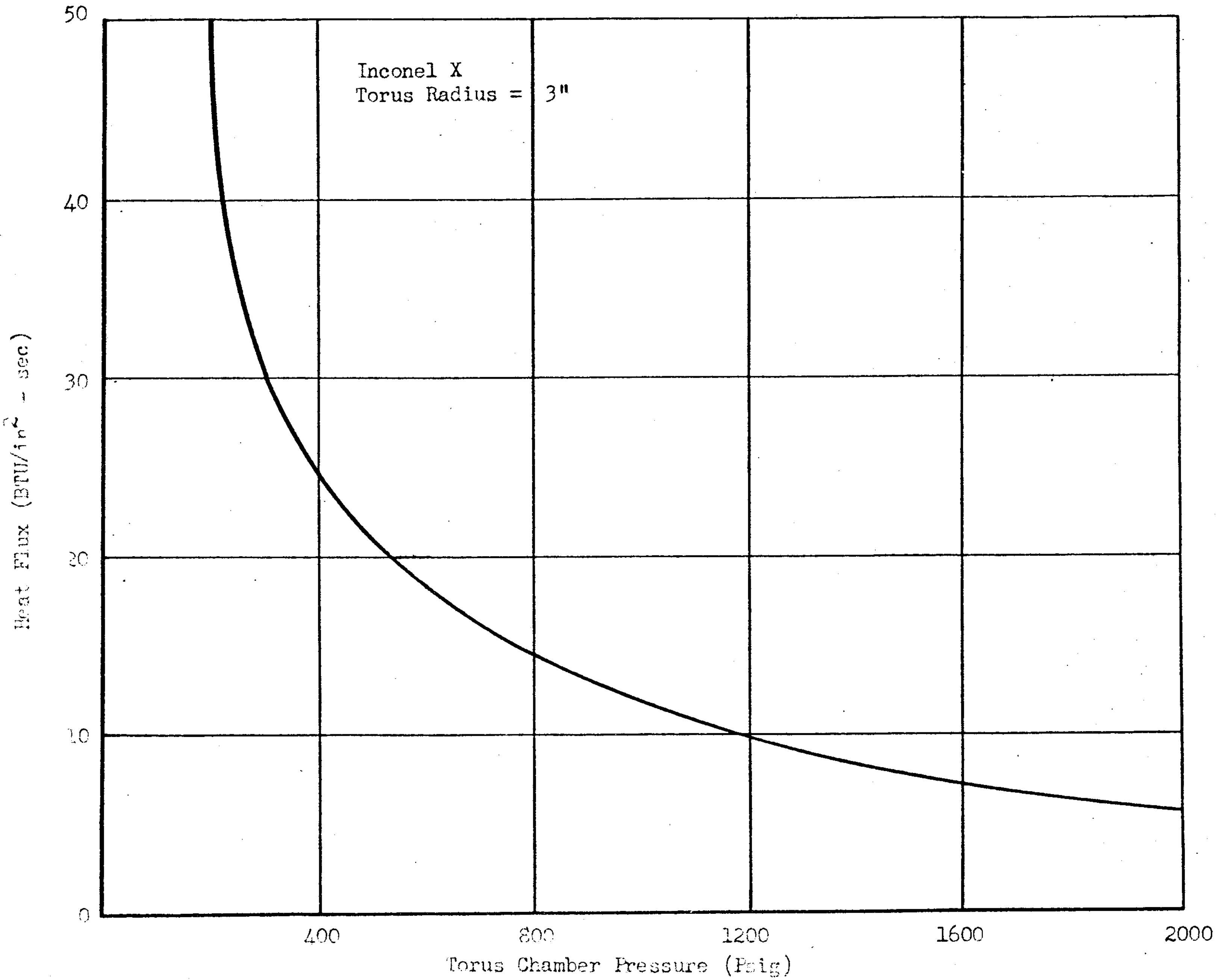

Figure 20 . Allowable Heat Flux vs Chamber Pressure

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Several material properties and geometrical parameters were found to have considerable influence on allowable heat flux. These include: thermal conductivity, mean wall temperature, yield stress, chamber radius, tube diameter, and tube contraction ratio. Generally, increases in thermal conductivity, yield stress, tube diameter, or tube contraction ratio will increase allowable heat fluxes; increases in mean wall temperature or chamber radius will decrease allowable fluxes. These effects are illustrated in the main text.

PARAMETRIC HEAT TRANSFER STUDIES

Parametric heat transfer studies were conducted to investigate the heating conditions in the throat region for the toroidal configuration. Several variables were considered. These included propellants, combustion chamber and tube geometry, and tube material. Equations for the peak heat flux (assumed to be at the stagnation point for the purpose of these studies) were derived, and the maximum heating rates in the toroidal were compared with those of bell chambers. Figure 21 indicates the results of these calculations, for a single chamber geometry, with oxygen/hydrogen and oxygen/kerosene propellants. For oxygen/hydrogen propellants, the peak heat flux in the toroidal chamber is greater than the bell chamber values for chamber pressures up to 4000 psia. For the oxygen/kerosene propellants, the curves cross at a lower chamber pressure and the heat fluxes in both chambers are nearly equal at low pressures.

The peak heating rate for a bell chamber is relatively invariant for a given chamber pressure and mixture ratio; however, the stagnation point relationship derived for the toroidal chamber is quite sensitive to geometry.

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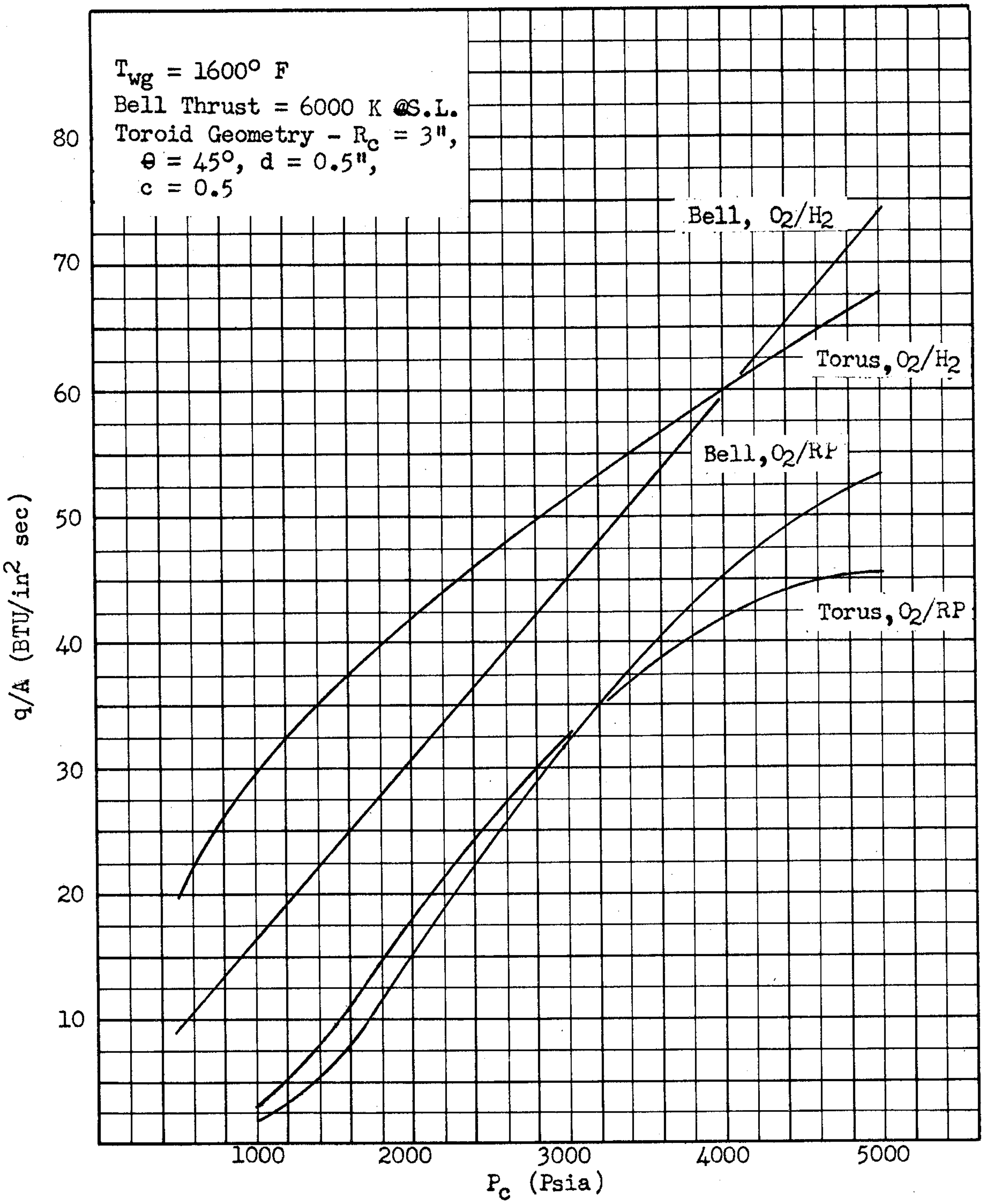

Figure 21 . Comparison of Heat Transfer Rates in Throat of Bell Nozzles and at Stagnation Point of Torus Tube.

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In general, substantial heat flux reductions can be achieved by either increasing the tube diameter (d_{tube}) or increasing the contraction ratio ($c = d_{throat\ tube}/d_{tube}$). For example, the peak toroidal heat fluxes indicated on Fig. 21 can be reduced approximately 30 percent by increasing the tube diameter from 0.5 to 1.0 inches. By increasing the contraction ratio and diameter simultaneously, a 50-percent reduction in heat flux can be achieved. These values indicate that for some geometries the stagnation point heat fluxes of the toroid, in fact, may be equal to or lower than comparable bell chambers. There is, however, some uncertainty about the point of maximum heat flux under such conditions. This point may shift from the stagnation point toward the throat region as chamber pressure increases or tube spacing changes. Currently, experimental results have indicated that for chamber pressures up to 450 psia the stagnation point of the tube is the region of greatest heat flux.

OPERATIONAL CAPABILITIES

By combining the heat transfer calculations (predicted heat flux) with the stress calculations (allowable heat flux) operational capabilities can be established. For example, with a specified chamber geometry and Inconel-X tubes, the stress and heat transfer data from Fig. 20 and 21 can be combined (Fig. 22). Thus, for the specified geometry and tube material, the recommended chamber pressure limit would be approximately 550 psia for oxygen/hydrogen propellants and 1400 psia with the oxygen/kerosene propellants.

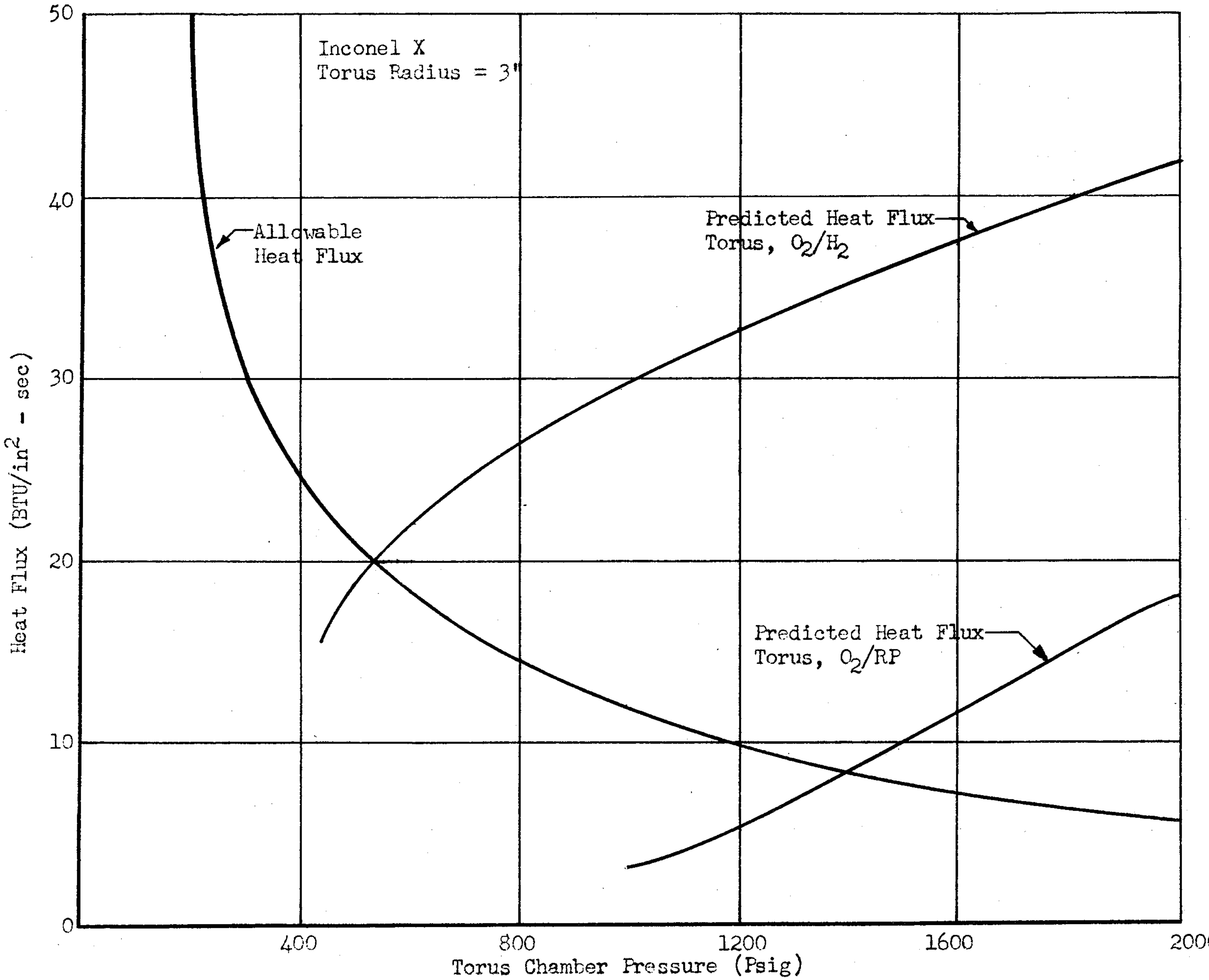

Figure 22. Sample Determination of Operational Capabilities With Regenerative Cooling

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Any factors which will alter either the allowable heat flux or peak heat flux will affect operational capabilities. Increasing tube diameter or tube contraction ratio has a favorable effect on operational capabilities, since peak heat fluxes will be reduced. However, increasing the combustion chamber diameter has a detrimental effect, since pressure stress and wall thickness increase, thus reducing allowable heat flux. The effects of these variations are described more completely in the main text of the report. However, the importance of these variables can be illustrated by examining the effect they have on operating conditions. For oxygen/hydrogen propellants with Inconel 718 tubes, the recommended regenerative cooling limits can range from 500 to 1100 psia by altering several geometric variables; and by using advanced tube constructions, the range can be increased to include chamber pressures over 1700 psia. For the oxygen/kerosene propellant combination and Inconel 718 tubes, regenerative cooling of chamber pressures up to approximately 1800 psi could be achieved with conventional tubing; and even higher values could be attained with advanced tube constructions.

Another factor that will influence the allowable heat flux curve is the amount of plastic strain in the tube. The previous statements have all been based on the assumption that neither the pressure stress nor the thermal stress individually will exceed the yield strength of the material. However, the combination of thermal and pressure stress will exceed the tube yield strength and introduce plastic strain. The occurrence of plastic strain in coolant tubes is not uncommon. Current conventional designs sometimes encounter up to 70-percent plastic strain. Figure 23 relates chamber pressure operating conditions to the percent of the plastic strain in Inconel-X tubes. In this case the criteria of not allowing thermal or pressure stresses

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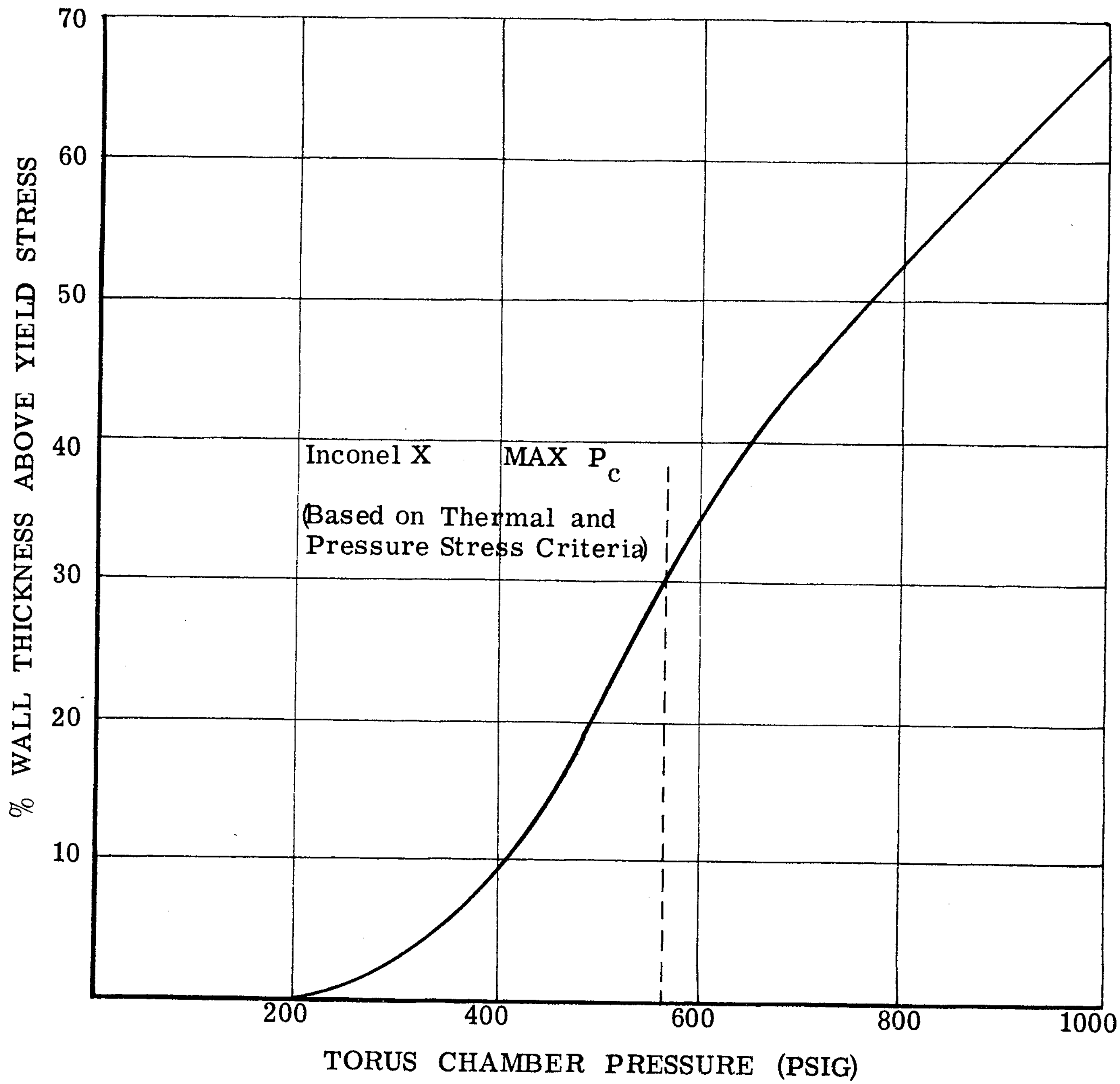

Figure 23. Percent of Wall Thickness With Plastic Strain for Toroidal Throat Tubes

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to exceed the yield strength produced approximately 30-percent plastic strain. The importance of defining the percent plastic when describing the operational capabilities of a toroidal tube is evident since increasing this percentage from 30 to 60 can increase the recommended maximum chamber pressure from 550 to 900 psi. However, since cycling capabilities are inversely related to the square of the percent plastic strain, a tube with 60-percent plastic strain would have one-fourth of the cycling expectancy of a similar tube operating with 30-percent plastic strain.

Since the tube thermal conductivity and yield stress will influence both the allowable and predicted heat fluxes, the selection of tube materials is very influential on operational capabilities. This effect is illustrated, for a given chamber geometry, on Fig. 24 . Here, several materials, including two refractory metals, are compared. Each material is represented by a bar. The clear portion of each bar is associated with the region in which regenerative cooling can be applied. A marking indicates the recommended maximum chamber pressure. This recommended maximum corresponds to the condition where neither plastic nor thermal stresses exceed the material yield strength. Regenerative cooling beyond this point is possible by operating at higher values of plastic strain. Operation beyond the clear area of the bar requires use of reinforced tube designs, ceramic coatings, or film cooling. Figure 24 indicates that for the given geometry conditions regenerative cooling can be achieved with conventional tubes up to 1000 psia. The refractory tubes can be used to regeneratively cool chambers operating at 2000 psia. These results may be used to indicate the qualitative effects of materials; however, as indicated previously, the absolute values of chamber pressure limits are highly dependent on geometrical effects, and frequently will exceed those indicated on the figure.

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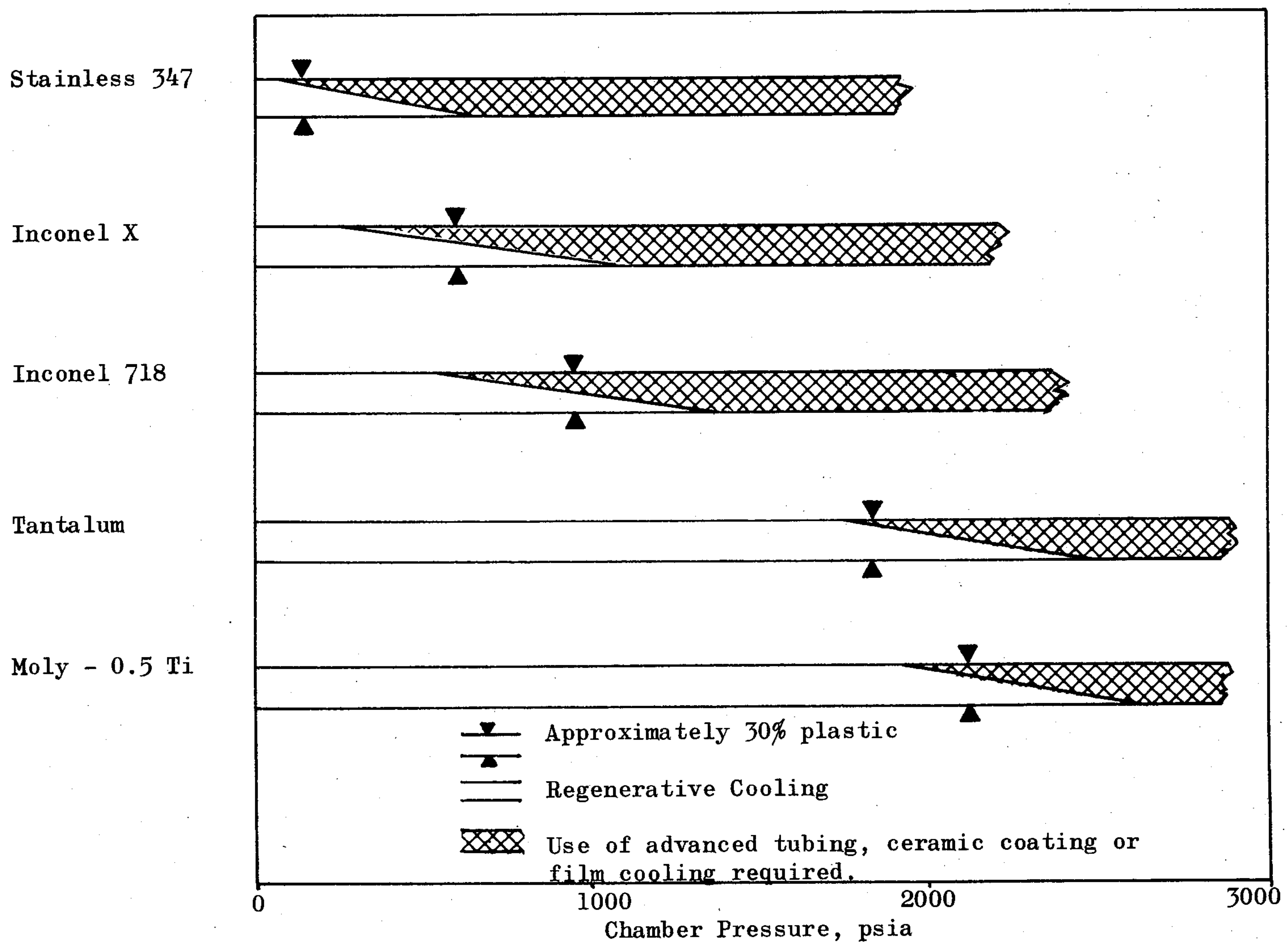

Figure 24. Recommended Operational Regions of Regeneratively Cooled Tubes (Propellants, O_2/H_2: Torus Radius, 3 inches)

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Operation at high chamber pressure can be achieved without the use of refractory metals by film cooling the chamber. Film cooling allows high-temperature operation for the toroidal chamber by decreasing the tube heat flux. The flow requirements to achieve total film cooling of the toroidal chamber are generally quite small. Calculations were completed to determine the amount of film cooling required for complete film cooling of a toroidal combustion chamber at a 2000-psia chamber pressure. The requirements were calculated by various techniques. However, the total requirement was usually less than 1 percent of the engine propellant flowrate. By combining regenerative cooling with film cooling, even smaller percentages of flow may be utilized.

COLD FLOW TEST DATA

Cold flow test data describing the stagnation pressures around the tube for various tube spacing were compiled. The first derivative of these data is related to the wall Mach number, and the second derivative is related to the heat transfer coefficient. It was therefore planned to employ measured pressures in calculating heat transfer coefficients for various tube spacings. However, careful analysis of the required computations indicated, that although pressure readings had been taken every 15 degrees of arc length around the tube, this would not provide sufficiently accurate derivatives in the stagnation point region. The calculations in this region must be extremely accurate to render conclusions valid. Analytical approaches to the problem in the region of the stagnation point have been disclosed by a literature search. The combination of an analytical solution near the pressure stagnation point and the measured pressure profiles in the other areas of the tube will provide a satisfactory technique for predicting tube heat transfer coefficients. At this time the equations and procedures for this analysis have been completed and programmed for future use. The results of this analysis will indicate the flow convection coefficient, the laminar-to-turbulent boundary layer to transition point, and the separation point of the flow from the tube, based on laminar boundary layer criteria.

TOROIDAL HEAT TRANSFER TESTS

A series of seven hot firing tests was conducted with a workhorse-type toroidal model. The primary objectives of these tests were to demonstrate concept feasibility, gather chamber and throat heat transfer data, and evaluate various tube materials. The propellants used in these tests were liquid oxygen and gaseous hydrogen.

The model (Fig. 25) uses the strip-type injector with two oxidizer streams impinging on one fuel. The combustion chamber is constructed of copper and is water cooled. The distance between the injector face and the chamber throat is 5.65 inches. End plates of the model are also constructed of copper and water cooled. Throat tubes are removable, and allow the testing of various tube samples. Fifty-two separate tubes were tested during the series. These included materials such as Inconel-X, Inconel 718, 347 and 327 stainless steel, tantalum, and TZM (99 percent molybdenum). Besides the range of materials, various tube thickness and coatings were also tested.

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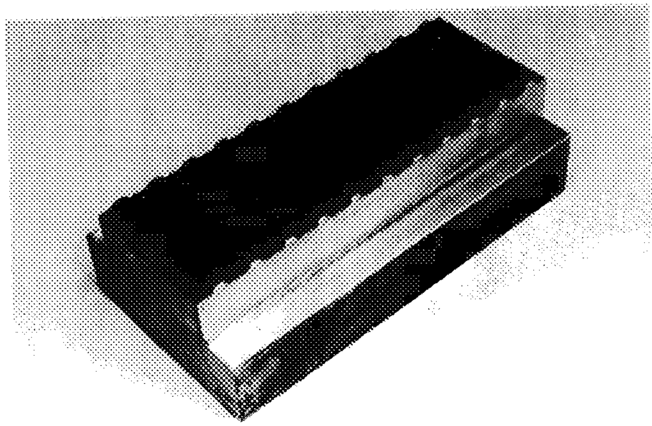
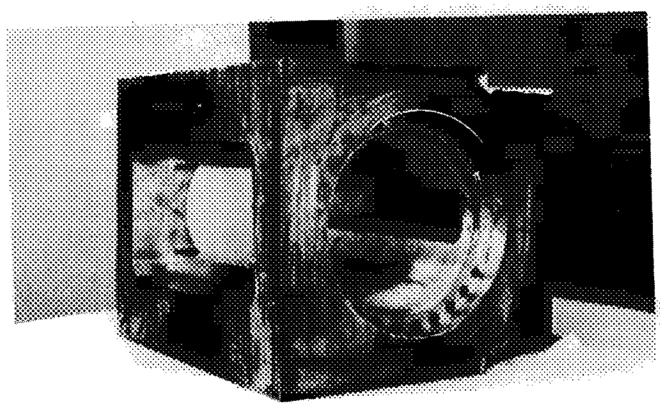
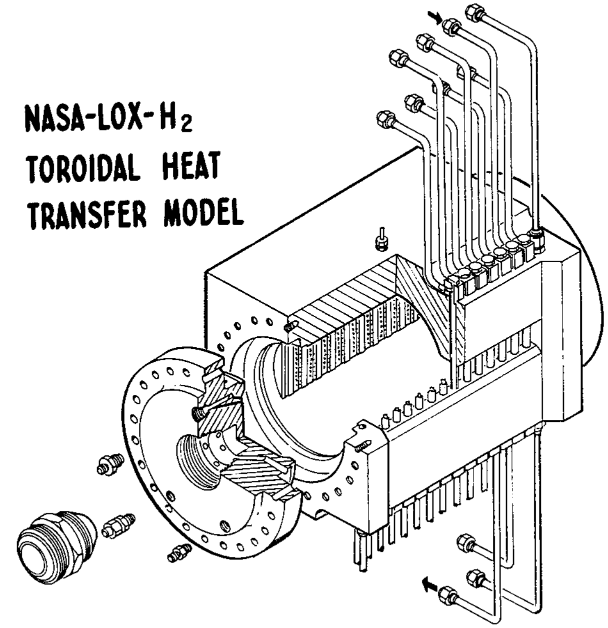


INJECTOR AND CHAMBER BEFORE BRAZING AND FINAL MACHINING



NASA-LOX-H_2 TOROIDAL HEAT TRANSFER MODEL



ASSEMBLY

Figure 25. Toroidal Heat Transfer Model

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During the tests in addition to the normal thrust, weight flow, and pressure measurements, numerous coolant flows and temperatures were monitored. These included the flows and temperature changes through a number of the chamber coolant passages and through each of the throat tubes. These measurements allowed the calculation of the average heat fluxes in the throat region and through various positions of the combustion chamber. Measured average heat fluxes in the throat tubes were generally slightly below predicted values. In the combustion chamber, heat fluxes near the injector were considerably below analytical predictions. This can be explained by assuming that combustion is not complete until the gases have partially passed through the chamber. In the portion of the chamber near the throat, the heat fluxes were somewhat higher than analytically predicted. This occurrence appears to be related to the injector type used during the test. It is assumed that the flow was not directed along the contour of the chamber and tended to impinge on the chamber areas near the throat. It was concluded that the pattern of the heat flux in the chamber will be closely related to the injection patterns used. However, the heat fluxes in the chamber will always be less than those encountered in the throat region.

In the hot-firing demonstration tests, the attainment of high performance was not a primary objective. Therefore, only one injector type was evaluated. Performance data have, however, indicated that c^* and I_s efficiencies in the range of 100 percent were attained during several tests. Some of the significant test results are listed in Table 2. Mainstage test durations varied from 0.8 to 5.8 seconds, an average of 3.5 seconds. Chamber pressure varied from 250 to 450 psia, and mixture ratio ranged from 3:1 to 8:1. The test stand installation and chamber operation during the sixth run are shown in Frontispiece C.

TABLE 2

PERFORMANCE DATA FROM TEST SERIES

Run Number	Duration, seconds	Thrust, pounds	Chamber Pressure, psia	Weight Flow, lb/sec	$\#_{c*}$	$\eta^{\#}_{I_s}$
1	-	480	105	-	-	-
2	0.8	3450	295	11.6	-	-
3	0.8	5150	450	16.6	-	-
4	3.0	3630	309	10.9	100	96
5	5.0	3580	292	11.9	101	100
6	5.8	5230	306	16.2	97	99
7	5.2	5700	314	16.5	100	101

#Based on frozen equilibrium for gaseous hydrogen and liquid oxygen propellants.

HEAT TRANSFER AND STRESS STUDY CONCLUSIONS

A few of the major conclusions that can be drawn from the heat transfer and stress studies are:

1. The peak heat fluxes in toroidal chambers are dependent on chamber pressure and chamber geometry. The analysis indicates that fluxes may be either higher or lower than comparable bell chambers.

2. Parametric studies indicate that regenerative cooling of oxygen/hydrogen combustion can be accomplished at chamber pressures up to 1100 psia; oxygen/kerosene combustion can be regeneratively cooled up to chamber pressures of 1800 psia. In each case even higher chamber pressures can be cooled with advanced tube construction.

3. Operation at high chamber pressures will require the use of refractory metals or film cooling. One percent of total propellant flow can film cool a chamber combusting oxygen/hydrogen at 2000 psia.

4. Experimental heat fluxes in the throat region are slightly less than theoretical predictions.

5. Heat fluxes in the combustion chamber region are closely related to the injector pattern. For the injector tested, experimental heat fluxes near the injector are less than analytically predicted; and experimental fluxes in the chamber near the throat are higher than analytically predicted.

6. Although combustion length (injector to throat) was relatively small (5.65 inches) and only one injector pattern was tested, high performance has been achieved with the toroidal hot firing model.